Hierarchical Subdivisions of the Columbia Plateau and Blue Mountain Ecoregions, Oregon and Washington

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ABSTRACT

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This document presents two spatial scales of a hierarchical, ecoregional framework and provides a connection to both larger and smaller scale ecological classifications. The two spatial scales are subregions (1:250,000) and landscape-level ecoregions (1:100,000), or Level IV and Level V ecoregions. Level IV ecoregions were developed by the Environmental Protection Agency when it became apparent that the resolution of national scale ecoregions provided insufficient detail to meet the needs of State agencies for establishing biocriteria, reference sites, and attainability goals for water-quality regulation. For this project, two ecoregions—the Columbia Plateau and the Blue Mountains—were subdivided into more detailed Level IV ecoregions. Similarly, the finer scale landscape-level ecoregions (Level V) were developed to address local land-management issues. The landscape-level ecoregions for northeast Oregon and southeast Washington were created specifically to address the issue of anadromous fish habitat. However, their delineation employed landscape information similar to that used in other levels of the ecoregion hierarchy, indicating the potential for general application of these regions to both terrestrial and aquatic research questions. The study area for the landscape-level ecoregions was defined by contiguous watersheds within the Columbia Plateau and Blue Mountain ecoregions to merge the ecoregional information with units corresponding to fish distribution.

Keywords: Ecoregions, anadromous fish habitat, fish habitat, watershed classification, landscape ecology, water quality, environmental mapping, classification.

CONTENTS

INTRODUCTION

Much of our disagreement about the proper role and function of regions, models and other generalizations probably should be attributed to basic and inherent differences between humans and their need for order, in which case it cannot be resolved by rational discussion. Most of us are probably somewhere on a continuum between two polar extremes. At one extreme are those tidy-minded souls whose instincts tell them that the world should move with all the precision of a finely tuned watch,. . .that our inability to detect regularity and order reflects our own weak analytical skills rather than the possibility that it may not exist. At the other extreme are those rambunctious types who perceive the world as a massive stochastic process, who glory in its disorder, chaos, and complexity, and who revel in the thought that every leaf on every tree is different. This battered old planet has quite enough evidence to keep both extremes happily convinced that they are right.

—John Fraser Hart, 1982

Background

The condition of the Columbia Plateau and Blue Mountain ecosystems is presently the focus of several Federal and State agencies. One hundred and fifty years of intensive land use—logging, road building, mining, grazing, and fire suppression—have transformed forests and grasslands, threatening the existence and long-term productivity of native ecosystems (Johnson and others 1994). Plans for restoration include more holistic management of forest, range, and water resources.

The concept of ecosystem management has gained acceptance among land management agencies, but implementing it can be a daunting prospect. It is difficult for resource managers to apply the results of many individual studies to broad areas. Different agencies have conflicting missions, overlapping jurisdictions, and administrative boundaries that restrict an ecosystem focus over all. Canadian resource managers have experienced the same difficulties; they have stressed the importance of an ecosystem perspective, arguing that the bulk of environmental research is concentrated on single-issue and single-medium subjects (Government of Canada 1991, Omernik 1995).

How do we move spatially and conceptually from single issue research to consider cumulative stresses and ecosystem response? To coordinate ecosystem management in environmental research, Federal land-management agencies formed an interagency task force to draft a Memorandum of Agreement that promotes the use of a common, hierarchical ecosystem framework. Existing ecoregion frameworks (Bailey 1983, 1994; Omernik 1987, 1995) provide the template for a common framework, by delineating areas of similar landscape characteristics that reflect the similarities in ecosystem type. By using a scheme that divides the landscape ecologically rather than administratively, agencies will be better able to develop strategies that are focused, ecologically significant, and thus, more cost-efficient. Federal agencies already have invested a great deal of time and effort in developing their own frameworks for particular objectives. It will be an arduous process to agree upon a common scheme; but if successful, it will be an important step toward coordinating research efforts.

Recent movement toward ecosystem management within Federal land management agencies has been prompted in large part by biological-diversity issues in forests of the Pacific Northwest. Following President Clinton's April 1993 Forest Conference in Portland, Oregon, various Federal agencies proposed initiatives to address problems with endangered species, remnant old-growth forests, poor forest health, and declining anadromous fish runs. The Eastside Forest Ecosystem Health Assessment and the Eastside Scientific Panel are addressing similar forest problems in eastern Washington, Oregon, Idaho, Montana, and Northern California (Everett and others 1993, Henjum and others 1994).

The interagency Forest Ecosystem Management Assessment Team (FEMAT) report (FEMAT 1993) lists four components of an Aquatic Conservation Strategy: the establishment of *riparian reserves* and *watershed refugia*, and *watershed analysis* as a foundation for *watershed restoration*. Ecoregion classifications at State and landscape scales will contribute to all of the components of the Aquatic Conservation Strategy by identifying groups of watersheds that are similar in ecosystem structure and by describing their expected condition.

A possible point of interagency contention is the tendency to consider watershed and ecosystem frameworks as mutually exclusive approaches. As a framework for research and planning, ecoregions provide a natural complement to watersheds. Spatial patterns in ecosystems or environmental resources continue across topographic divides (Omernik and Griffith 1991). In addition, streams may pass through multiple ecoregions, and their watersheds often change dramatically in character from headwaters to midstem to lowland sections. Figure 1 is an example of the interplay between ecoregions and watersheds (Bryce and Clarke 1996). Because streams B and C are within the same ecoregion, they probably have more in common than B has with stream A. Although A and B are located within the same watershed, they flow through distinctly different landscape types.

Data that offer no particular patterns when stratified by watershed may show patterns when stratified by ecoregion. Both frameworks should be applied for a full exploration of spatial patterns and management options; however, neither framework should be stretched beyond its ability to explain variability and patterns in the data (Bryce and Clarke 1996).

In this document, we report on the development and application of ecoregions at the two highest resolution levels of the five-level hierarchy developed at the U.S. Environmental Protection Agency (Omernik 1995). Level I and Level II classify ecosystems on a continental scale for the North American continent; Level III represents national scale ecoregions for the United States; Level IV regions are the more detailed ecoregions for State-level applications; and Level V are the most detailed ecoregions for landscape-level or local level projects. Further discussions of the development of this ecoregion framework may be found in Bryce and Clarke (1996), Clarke and others (1991), Gallant and others (1989), and Omernik (1987, 1995).

Ecoregion Methodology

Ecological regionalization is a form of spatial classification, the process by which boundaries are drawn around relatively homogeneous areas at a specific scale or level of detail. Ecoregions are developed through an iterative process that involves map analysis, the collaboration of regional experts, an extensive literature review, and a final integration of all available information. Physical characteristics such as climate, geology, geomorphology, historical and present-day vegetation, soil, land use, and hydrology are studied to determine the factors that reflect ecosystem character.

Map analysis is but one aspect of this approach. An extensive literature review adds an understanding of regional-level ecosystem processes and guides establishment of map units. Collaboration with regional experts from State and Federal agencies and academia is also essential to the process. This collaboration has the dual benefit of introducing field experience into the process, plus allowing input from those who might use the final product.

Finally, it is up to the geographer to integrate all of this disparate information. Innumerable critical judgments are made based on research and experience. The product is not the result of a mechanical overlay of maps; the computerized geographic information system is merely a tool to aid in analysis and final display. The final ecoregion map is an interpretation or model of reality. Boundary decisions may represent a different suite of landscape characteristics from one area of a region to another, depending upon the shifting dominance of the landscape characteristics. Some of the boundaries represent present-day conditions, but some represent conditions that no longer exist. Modeling the historic condition has applications for distinguishing how far human impacts have taken the ecosystem from a more unmanaged condition. Discussions of individual boundary decisions in the chapters to follow will further address this issue.

The ecoregion delineation is completed by drawing lines directly onto 1:250,000 or 1:100,000 scale topographic maps for digitization, correcting for topography where appropriate to produce a precise line. An additional map has been developed that depicts the boundary transition widths (a "fuzzy boundaries" map) (Clarke and others 1991, Griffith and others 1994). An example of a fuzzy boundary map of the Columbia Plateau Level III and Level IV ecoregions is included in section 1 (fig. 3).

Applications of the Ecoregion Framework to Resource Management

Because they are constructed through the use of many data sources, ecoregions do not have a specific theme, and thus, they have the potential for general application. While they may not explain the response of any single ecological element, such as a particular species distribution, they do represent an area of relative homogeneity in landscape characteristics (Bryce and Clarke 1996). The ecoregion framework is an organizational tool that may enable resource managers to apply an ecosystem approach to assessment, monitoring, and research, and thus transcend administrative boundaries. Several of the most widely used applications of ecoregions are listed below:

Sampling design—In order to plan a monitoring program, there may be a need to group a population of similar sites together from which a representative sample may be chosen. The size and heterogeneity of a region indicates the appropriate number of sites required to adequately represent an area. Fewer sites per unit area will be needed in homogeneous landscapes and more in heterogeneous landscapes. Identification of ecoregions aid in determining the density of the sampling frame to ensure that important areas are not missed.

Ecoregions tend to run laterally across large topographic basins, particularly in some mountainous areas. The headwaters, midstem, and mainstem of larger streams and rivers may traverse different terrain types represented by unique ecoregions (fig. 1). To capture the range of conditions, sites from multiple watersheds within each ecoregion can be grouped. Though no two sites are exactly alike in physical characteristics or quality, a group of sites within an ecoregion tend to be similar.

With a hierarchical regional framework, the scale of ecoregion may be chosen to fit a particular project. Ideally, the scale should fit the type of data being gathered, the spatial extent of sampling, and the research questions being asked.

Data analysis—The stratification of sites and sampling information into relatively homogeneous groups reduces apparent variability and increases precision in data analysis. Once the regional boundaries have been shown through field testing to be representationally accurate, the regions provide a defensible area in which site-specific results may be extrapolated. In this way, local project results may be applied to broader scale resource management. Ecoregions lend a predictive capacity to management decisions through the assumption that a subpopulation of sites within a relatively homogeneous region will respond similarly to a specific type of management.

Water quality standards—Ecoregions have been used by states to structure their water resource monitoring and assessment programs (Heiskary and Wilson 1989, Larsen and others 1988, Rohm and others 1987). With a spatial framework, water resource managers are able to set regionally appropriate management goals for lakes and streams and design programs for nonpoint source pollution abatement and reduction of effluent discharges. Setting water quality standards regionally means that streams are less likely to be either over- or underprotected as they may with a single nationwide or statewide standard.

Reference condition and ecosystem restoration—Ecoregions provide a framework for locating waterbodies to serve as reference sites. Reference sites can be chosen from within any scale in the ecoregion hierarchy. As a benchmark for attainable conditions, a reference site should be both regionally representative and relatively unimpacted (Gallant and others 1989, Hughes and others 1986). Reference areas, chosen within a regional framework, are representative of a particular population of streams and serve as a model of attainable condition. Until now, water resources have been the focus of the regional reference site concept. However, with the increasing interest in ecosystem management, there is an opportunity to expand the implementation of the concept to relatively unimpacted terrestrial sites that are representative of the landscape character of the ecoregion.

Rehabilitation of disturbed sites can proceed most effectively if there is a measurable goal represented by the reference site, even if that goal is not completely attainable. Other sites of varying disturbance can be compared with this model and ranked along a continuum of condition. Relating present condition to the potential capability of the systems contributes to the search for the probable causes of condition. Once probable causes of degradation are identified, managers can set priorities for cost-effective restoration.

Scope of Work

This introductory section presented the rationale and methodology employed in the ecoregion process as well as applications of the ecoregion framework. The next two sections, 1 and 2, describe Level IV ecoregions displayed in the accompanying map for the Columbia Plateau and Blue Mountain ecoregions. Photographs 1 to 16 in figure 2 depict the Level IV ecoregions. The complexity and relative importance of factors considered in the development of ecoregions varied greatly between these two ecoregions. The same landscape characteristics were considered in each ecoregion project, but different combinations of factors tended to dominate depending upon the character of the region For example, the landscape of the Columbia Plateau is a product of a dramatic series of events during the Pleistocene (Bretz 1969). Its ecosystems are a reflection of the arid climate, soil, glacial geomorphology, and fluvial erosion. The clarity of these features made the regionalization of the Columbia Plateau relatively straightforward. The greater difficulty there arises from applying an ecosystem framework to an intensively farmed, largely privately owned, arid region. In the Blue Mountains, on the other hand, the dominant factors are climatic and elevational gradients imposed upon an extremely complex geology. The complexity of the landscape and the general lack of biological, geological, and climatic information, particularly in higher elevations, makes this project a first iteration of an ongoing refinement of ecological regions there.

Section 3 describes the development of landscape-level ecoregions (Level V) for seven contiguous watersheds in northeastern Oregon and southeastern Washington located within both the Columbia Plateau and Blue Mountain Ecoregions. The Bonneville Power Administration (BPA) is required by law to restore anadromous fish runs to compensate for fish losses incurred at dams on the Columbia River (Pacific Northwest

Electric Power Planning Act 1980). The BPA funded this project to develop landscape-level ecoregions as a means to help define expected habitat conditions. The project is an effort to stratify a complex area into more homogeneous units that may have similar potentials and reactions to stressors. In this section, we outline the connection between stream habitat characteristics and landscape characteristics, and we describe how each of the major landscape characteristics might affect fish habitat. Figure 2 illustrates the connection between the Level IV and Level V ecoregion hierarchy. Photos 1 to 5 and 6 to 16 depict the Level IV ecoregions of the Columbia Plateau Ecoregion and Blue Mountains Ecoregion. To demonstrate the variability within these subregions, represented by landscape-level ecoregions (Level V), photos 21 to 27 show the diversity within the Maritime Subregion, and photos 27 to 29 show the diversity within the Canyons and Dissected Highlands Subregion.

The landscape-level ecoregions described in Section 3 were developed specifically for anadromous fish habitat research and management (Bryce and Clarke 1996). However, the methodology and types of data sources are the same as those used in ecoregion delineation at broader scales in the hierarchy. For this reason, we believe that the classification may have broader application to other resource issues. The full complement of regions at a particular scale may not be necessary for a specific project; regions may be aggregated depending upon the objectives of the project. The rationale for making boundary decisions has been discussed in detail, which should help in assessing the usefulness of the classification for other resource issues.

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SECTION 1—LEVEL IV ECOREGIONS OF THE COLUMBIA PLATEAU ECOREGION OF OREGON, WASHINGTON, AND IDAHO

by Sandra A. Bryce and James M. Omernik

Columbia Plateau Ecoregion/Subregion Project

The impetus for the Columbia Plateau regionalization project was a mutual concern of EPA Region X, the Washington Department of Ecology, and the Oregon Department of Environmental Quality to better frame management decisions about nonpoint-source (NPS) pollution. The agencies also agreed that the refinement of ecoregion lines, the delineation of subregions (Level IV ecoregions), and the selection of reference sites were prerequisites for establishing biocriteria standards in portions of Oregon, Washington, and Idaho. An ecosystem-based framework also afforded the opportunity for the three States to share data and assessment results in regions of similar natural capacities. Though the original project had a water quality focus, ecoregions are delineated using terrestrial landscape information; thus, they have the potential for terrestrial applications as well.

Although geographers at EPA's National Health and Environmental Effects Laboratory, Western Ecology Division (NHEERL-WED) in Corvallis, Oregon, were responsible for the final delineation of ecoregion boundaries, the Columbia Plateau project was a collaborative effort with State resource managers and regional experts. Meetings and phone consultations were held with State and Federal agency personnel and members of academia to review progress and exchange ideas. Such qualitative input was critical to the creation of a regional framework that will be meaningful to those using it. Continued collaboration is also necessary for the evaluation of the boundaries derived from the geographic data.

Description of the Columbia Plateau Ecoregion

The arid nature and earth-toned landscape of the Columbia Plateau belies the spectacular origins of its topography. The Columbia Plateau was shaped by episodic geologic events of epic proportions. During the Miocene epoch, between 17 and 6 million years ago, lava flows erupted from vents in southeastern Washington and northeastern Oregon to fill the basin with lava up to 2 miles thick. As many as 200 separate flows eventually covered an area approximately 160,000 square kilometers (Baker and others 1991). The earth's crust gradually sank under the weight of the lava, producing the sloping Columbia Plateau (Allen and others 1986). During the Pleistocene, a continuous covering of loess was aerially deposited over the basalt. Because of the area's general saucer shape, sloping from its edges to the low point in the Pasco Basin, the Columbia Plateau is often called the Columbia Basin. However, since the term "basin" also indicates drainage area and to avoid confusion hereafter, the region will be called the Columbia Plateau ecoregion in this report.

The features on the surface of the plateau were sculpted during the Pleistocene.

Those features that are most discernible are thought to have occurred between 12 and 15,000 years ago during the last advance of continental glaciers (Allen and others 1986). Periodically during this time, the Clark Fork River in Montana was dammed by a lobe of the glacier, forming the huge Lake Missoula, which covered 3000 square miles (4825 sq km) of intermountain valleys in Montana. Rising waters regularly breached the ice dam sending huge quantities of water surging across the Columbia Plateau. These floods varied in intensity, but the largest are said to have contained up to 10 times the flow of all rivers in the world or 60 times the flow of the Amazon River (Allen and others 1986, GS 1982). The flood channels cut through the thick deposits of windblown soil, leaving islands of loess separated by scablands and bedrock channels.

Attributing the topography of the Plateau to massive flood events was the painstaking and controversial life's work of geologist J. Harlan Bretz, who crossed much of the scabland country on foot, mapping as he went and piecing together the evidence of the Missoula floods (Allen and others 1986). What took Bretz 40 years to compile we can now visualize in an instant with the aid of satellite imagery—the mammoth braided channels crossing the entire plateau from northeast to southwest.

The Columbia Plateau is an arid shrub/grassland surrounded on all sides by forested mountain ranges: the Cascade Mountains to the west, the Okanogan Highlands to the north, the Blue Mountains to the south, and the Rocky Mountains to the east. The climate of the Columbia Plateau is continental with a marine influence. Summers are hot and dry with most of the precipitation falling during the winter months. Precipitation increases across the plateau from southwest to northeast. It is lowest in the basins on the western side of the plateau, where the rain shadow effect of the Cascade Mountains limits precipitation to 15.2 to 22.9 centimeters per year (6 to 9 in per yr). Rainfall gradually increases to the east with higher elevations and proximity to the Rocky Mountains and Blue Mountains.

Temperature, moisture, and mineral content determine soil formation, and the texture affects the rate at which complex soil horizons, organic matter, and clay layers develop (SCS 1981a). The lack of moisture on the Columbia Plateau results in soil low in organic matter and clay. Depending on their location, soils of the Columbia Plateau may be derived from basalt colluvium on hillslopes and canyon walls, alluvium from valley floors, or gravelly flood deposits and glacial outwash. However, the predominant soil of the Plateau is loess. Loess forms a large deposit called the Palouse Formation that covers the entire area of the Columbia Plateau to depths of 75 meters (22.9 ft) in the southeastern Palouse Hills (Baker and others 1991). It is of granitic and metamorphic origin, transported by glaciers from the Rocky Mountains to the east and north and redeposited by prevailing southwesterly winds over the past 50,000 years (Baker and others 1991, SCS 1981a).

Gradually increasing precipitation toward the northeast influences the dryland agricultural capability of the loess soil. Cropping techniques vary from a 2-year winter wheat/fallow rotation in areas with 22.9 to 38.1 centimeters per year of precipitation (9 to 15 in) to a 3-year winter wheat/spring barley/fallow in areas receiving 38.1 to 45.7 centimeters per year of precipitation (15 to 18 in) (SCS 1981b). Annual cropping on unirrigated land is only practiced in the Palouse Hills, where moisture levels reach 45.7 to 58.4 centimeters per year (18 to 23 in per yr). Loess is highly productive, but it is also highly erosive. In the heart of the Palouse River basin, farming on steep slopes and farming practices such as clean tilling fallow fields leads to average erosion rates of 44.8 tons per hectare (20 tons per ac) through rill and sheet erosion during the wet season (Steiner 1987).

The type and amount of vegetation of the Columbia Plateau also varies with temperature and moisture. The low precipitation amounts and negligible yearly runoff combined with high evapotranspiration and deep, dry loessial soil create an environment ill-suited to tree growth. Though the Plateau has been called a desert, Daubenmire (1970) described it as a steppe. He defined a desert as a region too dry to support grassland and a steppe as a region with enough moisture to support grasses but not trees. According to this definition, the Columbia Plateau is a grassland steppe. Daubenmire has divided the Plateau into nine vegetation zones. The big sagebrush/bluebunch wheatgrass and big sagebrush/Idaho fescue associations occur in the driest core of the Plateau. Grasses without the sagebrush element grow in the slightly wetter eastern portion of the Plateau. The other five associations appear around the perimeter of the Plateau in the lusher meadows of grasses, broad-leafed forbs and shrubs that form the transition to forest. The shrub element varies from bitterbrush in the eastern Cascade foothills to snowberry sp. in the Rocky Mountain transition zone.

There is no evidence that the plant life of the Columbia Plateau has evolved under either a grazing or a fire regime. The bunchgrasses will tolerate light grazing after seed formation. They do not recover after heavy grazing but are replaced by alien grasses, such as cheatgrass (*Bromus tectorum*). The brushy species, on the other hand, are sensitive to fire. It is unlikely that large herds of grazing animals roamed the Plateau as they did the Great Plains or that the original inhabitants used fire as a hunting strategy (Daubenmire 1970, Franklin and Dyrness 1974).

In summary then, the Columbia Plateau differs from adjacent mountainous, forested ecoregions in its aridity, its low relief, and its lack of trees. However, no single attribute described above, not geology, climate, topography, soil, or vegetation, is sufficient to determine the ecoregion boundaries of the Columbia Plateau. For example, the flood basalts that comprise the Columbia Plateau also form the foundation of the Blue Mountains to the south. The Blue Mountains ecosystem is very different from the Columbia Plateau, yet large portions of it have the same geology. As a result, geology is not useful for making the southern ecoregion boundary decisions. Similarly, vegetation is not a dominant feature in boundary decisions in the Deschutes River area of Oregon. Similar vegetation associations occur just to the south in the high desert area of Oregon (as they do in southern Idaho and Montana). Producing a map of ecological regions requires integrating all of the landscape characteristics and developing a rationale for the boundaries that is consistent with the projected uses for the ecoregions. In this way, ecoregion maps differ from thematic maps which seek to define the distribution of a single characteristic.

Materials

Component maps and data for the Columbia Plateau project were assembled from the participating States, from EPA's NEERL-WED map library, and from Oregon State University's map library. Additional information, such as historical documents, satellite images, and pertinent published articles, contributed to the refinement and evaluation of subregion boundaries.

The data that was most useful for the subdivision of the Columbia Plateau ecoregion were maps of geology, soil, potential vegetation, topography, and land use/landcover. Digital coverages at 1:250,000 scale from a series of soil maps (STATSGO) were acquired from the U.S. Department of Agriculture's Soil Conservation Service (Note: in late 1994, USDA changed the name of SCS to the National Resources Conservation Service [NRCS]). These maps were supplemented by existing county level 1:24,000 scale soil maps and texts (cited at the end of this section under SCS by year). A present-day vegetation map of Oregon sponsored by the U.S. Department of the Interior's Fish and Wildlife Service (FWS) was also available in digital form from the

Idaho Department of Water Resources. This map was supplemented with smaller scale maps of Oregon and Washington vegetation and literature about the vegetation communities of the Plateau. Geological information was provided by a 1:500,000 scale map of Oregon, both digital and hard copy (Walker and McLeod 1991) and 1:250,000 scale geologic maps of the northeast and southeast quadrants of the State of Washington (Schuster 1995, Stoffel and others 1991). U.S. Department of the Interior, Geological Survey (GS) land-use maps were available in digital form. Finally, at 1:250,000 and 1:100,000 scale, GS topographic maps were indispensable for the interpretation of land surface form, drainage pattern, contour intervals, gradient, aspect, and elevation. Topographic maps serve as a reality check for the other maps, especially those that have been interpreted, such as the soil, geology and vegetation maps. The ecoregion boundaries were delineated and digitized using the 1:250,000 scale topographic maps as base maps.

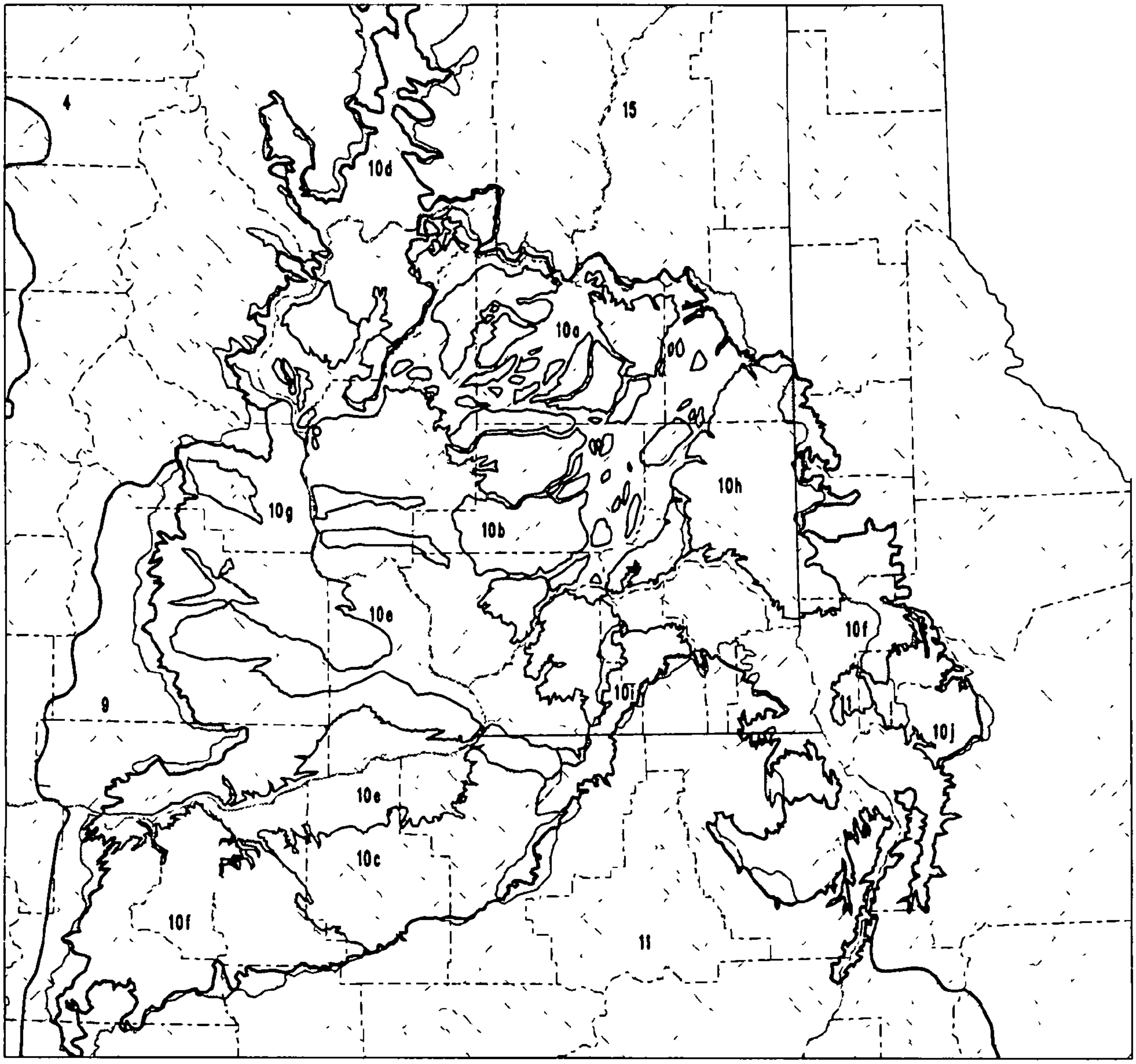
Ecoregion Boundary Decisions

During the regionalization process, some boundaries between distinctive ecoregions or subregions appear obvious whereas others are more difficult to determine. For example, the Channeled Scablands subregion of the Columbia Plateau is determined by the clearly visible boundaries of flood channels gouged out of the landscape. Other boundaries are not so readily apparent; their delineation requires an accompanying rationale, which is the result of integrating the multiple source materials. These less-apparent boundaries, such as those at the change from grassland to forest at the perimeter of the Plateau, represent transition areas of various widths along ecological gradients. One method of mapping this phenomenon is through the use of "fuzzy boundaries" (Clarke and others 1991). A boundary transition width map is included with the ecoregion/subregion map for the Columbia Plateau (plate 3). Sites near region boundaries, especially in transition areas, tend to have characteristics of both regions. Field visits are necessary to determine which regional characteristics dominate at sites of interest.

Other boundary considerations arise because of variations in the extent that human activities have changed the landscape. In an attempt to have boundaries represent relatively constant conditions, ecological regions are defined on the basis of potential capability. As Daubenmire found when trying to relate the distribution of vegetation to climate patterns (Daubenmire 1956), the correlations between climate and vegetation were meaningful only where vegetation boundaries were relatively stable. He knew that fossil-pollen studies indicated that very little climate-induced change had occurred in plant distributions since the end of the last glacial advance. However, the high frequency of human changes and the extirpation of species confounded his search for patterns.

Anthropogenic changes in the Columbia Plateau have continued unabated since Daubenmire's investigations in the 1950s. Large irrigation projects across the driest parts of the Plateau, once known as the "Great Inland Desert," have markedly changed the groundwater and surface-water patterns. Areas irrigated with surface water from

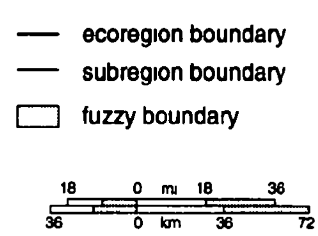
COLUMBIA PLATEAU ECOREGION/SUBREGION BOUNDARY TRANSITION WIDTHS



COLUMBIA PLATEAU (10)
- Channeled Scablands (10a)
- Scabland loess islands (10b)
- Umatilla plateau (10c)
- Okanogan drift hills (10d)
- Pleistocene lake basin (10e)
- Canyons and dissected uplands (10f)
- Yakima folds (10g)
- Palouse hills (10h)
- Deep loess foothills (10i)
- Nez Perce prairie (10j)

CASCADES (4)
EASTERN CASCADES SLOPES AND FOOTHILLS (9)
BLUE MOUNTAINS (11)
NORTHERN ROCKIES (15)

This map illustrates the relative widths of ecoregion and subregion boundaries. Regional boundaries are usually portrayed by single narrow lines on maps, but they represent transition zones of varying widths on the ground, where characteristics of one area blend with those of another The map shows how broad or narrow the transition areas appear to be as indicated by component maps and other sources of information



the Columbia and Yakima Rivers are experiencing a dramatic increase in the amount of groundwater and excess irrigation runoff. For example, the extent of marshland has greatly increased in the Potholes region near Moses Lake, Washington. Long-term groundwater recharge estimates, covering the period 1956 to 1977, for both predevelopment and modern land-use conditions in the core area of the Columbia Plateau, showed an increase of 5.7 centimeters per year (2.23 in per yr) on average in the rate of groundwater recharge. For the zone covering the Moses Lake area, recharge increased from 1.45 centimeters per year (0.57 in per yr) to 25.6 centimeters per year (10.07 in per year). Conversely, in areas that are irrigated from wells, water withdrawals have caused a decrease in recharge across the zone (Bauer and Vaccaro 1990).

These dramatic changes have not been incorporated into the boundary decisions for subregion lines. Although it is likely that wide areas of the Columbia Plateau will never return to their original condition, we cannot gauge the extent of the human induced changes to ecosystems unless we use a model of the presettlement condition as a guide. There is enough information available on temperature and precipitation regimes, soil and native vegetation to reconstruct the boundaries of the presettlement ecosystems. Human caused changes, such as the modifications in groundwater and surface runoff in irrigated areas, or the dominance of cheatgrass and other alien plants across the formerly discrete vegetation zones of the plateau, can be treated as a separate layer of information which is superimposed upon the model of ecosystem potential.

Description of the Columbia Plateau Subregions

The ecoregions described in table 1 are presented in the map of the Columbia Plateau subregions (fig. 3). Native vegetation of the Columbia Plateau has been listed in table 1.

Channeled scablands and Loess Islands (fig. 2, 10a; fig. 3, 10a and 10b)—The Channeled Scablands were formed as immense floods periodically broke through the ice dams blocking glacial Lake Missoula during the Pleistocene. The immense quantity and high speed of the surging water scoured away the loess covering the Plateau as well as portions of the underlying basalt bedrock. The vertical jointing of the basalt makes it susceptible to "plucking." This phenomenon can be seen in the steep vertical walls of the flood channels, in the numerous small lakes, called kolk lakes, gouged out of the basalt surface, and in the giant plunge pools created at huge cataracts. In the northwest part of the Plateau, the scabland channels, such as Grand Coulee and Moses Coulee, also served as outflow channels for glacial Lake Columbia and the Okanogan lobe of the Wisconsin ice sheet.

Patterned ground covers the basalt plateaus bordering the main flood channels. These "scabs" are composed of mounds of loess surrounded by rock fragments. The soil is a thin veneer 0 to 62.5 centimeters (0 to 25 in) on the basalt surface of the scablands (SCS 1981b).

These scabland tracts cover gently sloping topography. Elevations increase 7.6 meters per kilometer (25 ft per mi) across Lincoln County in the central part of the Plateau (SCS 1981b). Precipitation amounts range from 17.8 to 45.7 centimeters per year (7 to 18 in per yr) from west to east. The scablands are too dry to support trees except in the Cheney area on the far east side of the Plateau, where the absence of loess and more abundant precipitation allow ponderosa pines to root in the fractured basalt (Hooper and Reidel 1989). The most common native vegetation of the scabland channels is the stiff sage/bluegrass association. The present day land use is grazing.

The Loess Islands are the post-flood remains of the once unbroken mantle of wind-deposited silt (loess) that covered the entire Plateau. The loess islands range in size from small scraps to more than 1000 square kilometers (622 sq mi). The loess is thinner across the central and western portions of the Columbia Plateau than it is in Palouse Hills to the east. Future investigations of the stratigraphy of loess islands may clarify the timing of the flooding episodes (Baker and others 1991). Precipitation in the Loess Islands subregion ranges from 17.8 to 45.7 centimeters per year (7 to 18 in per yr) from west to east across the Plateau. The distribution of native vegetation generally follows this change in moisture availability. The big sage/bluebunch wheatgrass association grades into the bluebunch wheatgrass/Idaho fescue association as precipitation increases. A different sage species, threetip sage, grows with Idaho fescue in a wide band around the northern perimeter of the Plateau, roughly in the 12 to 18 inch (30.5 to 45.7 cm per yr) precipitation range. As in the other meadow steppe communities on the fringes of the plateau, the threetip sage and Idaho fescue form a lush complex with a wide variety of broad-leafed forbs.

Present day land use has transformed the loess islands into wheatfields. Cropping systems vary according to precipitation amount. The drier areas (22.5 to 37.5 centimeters per year [9 to 15 in per yr] precipitation) are farmed in a winter wheat and fallow rotation; and the wetter areas (37.5 to 45 centimeters [15 to 18 in per yr] precipitation) are managed in a winter wheat, spring barley, and fallow rotation.

Umatilla Plateau (fig. 3, 10c)—The Umatilla Plateau is bounded on the north by the basin of glacial Lake Condon, on the west by the eastern slopes of the Cascades, and on the south by the transition of nonforested loessial soil to the forest soils of the Blue Mountains. Precipitation increases with increasing elevation, from 20.3 centimeters per year (8 in per yr) at the margin of the glacial lake basin to 58.4 centimeters per year (23 in per yr) at the upper elevations. Because the Umatilla Plateau begins above the drier glacial lake basin, sagebrush is not a significant member of the plant community. Grasses, bluebunch wheatgrass, and Idaho fescue predominate throughout the Umatilla Plateau. Fescue dominates in higher areas with greater precipitation and on steeper northern slopes (Anderson 1956). In the grassland to forest transition zone, shrubs such as rose, hawthorne, and snowberry mingle with the grasses.

The soil and landform patterns of the Umatilla Plateau follow concentric levels of terraces rising to the Blue Mountains in the south. From north to south, the deep loessial soils (Walla Walla and Ritzville) become thinner (Condon and Morrow) as the rolling wheatfields become interspersed with flatter areas of patterned ground. The Blue Mountain foothills and piedmont alluvial fans have a very thin loess covering and steeper slopes. The soils on these upper terraces (Gurdane and Gwin) contain a higher component of basaltic rock fragments. Here the land-use changes from wheat farming to grazing on thinner soils (SCS 1988). It is reasonable to assume that the rest of the Columbia Plateau once resembled the Umatilla Plateau, before the massive Missoula floods rearranged the loess mantle, creating the channeled scablands and lacustrine deposits.

In the western section of the subregion, the tablelands isolated by the Deschutes and John Day river canyons are broad enough to support dryland wheat farming. A traveler on these isolated tablelands is unaware of the canyons falling away on either side. The southern boundary on the western end of the Umatilla Plateau is marked by the change from loess-dominated soils to the clays derived from the ancient sedimentary deposits of the John Day Formation. Juniper appears on this soil type and marks the westernmost extension of the Blue Mountains/High Desert area of central Oregon (Anderson 1956).

Okanogan Drift Hills (fig. 3, 10d)—The Okanogan Drift Hills subregion, located in the northwest corner of the Columbia Plateau ecoregion, follows the valley of the Okanogan River north to the Canadian border. The Okanogan lobe of the Wisconsin Glacier advanced far enough down the valley to dam the Columbia River, creating glacial Lake Columbia and rerouting the Columbia River through Grand Coulee. As the glacier melted, it retreated up the Okanogan valley, leaving behind a blanket of glacial till. The till, up to 15.2 meters (50 ft) thick, is composed of clay, silt, sand, gravel, cobbles, and boulders. Though the region has a thin veneer of loess on top of the till, the characteristic deep loessial soil of the Plateau has been transformed by glacial action. Classic glacial features such as drumlins, kames, eskers, terminal moraines, and kettle ponds are common.

The Okanogan valley lies in the rainshadow of the North Cascade Mountains. Rainfall in the valley bottom is 22.9 to 30.5 centimeters per year (9 to 12 in per yr), the same as in the Pasco Basin to the south. Rolling uplands bordering the valley reach elevations of 912 meters (3000 ft) with precipitation of 27.9 to 38.1 centimeters per year (11 to 15 in per yr). In the valley bottoms, present day land use includes irrigated agriculture and orchards. The uplands support dryland wheat farming and grazing.

Native vegetation includes big sage and bluebunch wheatgrass in the drier areas and the threetip sage/Idaho fescue association in the moister uplands. West of the Okanogan River, bitterbrush grows with the fescue as the upper grassland-to-forest transition association. In the higher elevations of the Okanogan highlands, the sagebrush is replaced by a fescue/forb groundcover in mountain meadows (Daubenmire 1970). At elevations where precipitation exceeds 40.64 centimeters (16 in), ponderosa pine grows with a fescue and bitterbrush understory. The boundary denoting treeline, or the presence of forest soils in areas cleared for agriculture, forms the east and west boundaries of the Okanogan Drift Hills subregion. The southern boundary follows the Pleistocene glacier's terminal moraine along Dutch Henry Draw in Douglas County. This subregion is the southern extension of a glaciated ecoregion in Canada covering the Okanogan country of British Columbia.

Pleistocene Lake Basins (fig. 2, 10e; fig. 3, 10e)—Vast temporary lakes formed periodically with the release of flood waters from glacial Lakes Missoula and Columbia during the Pleistocene. Lake Lewis formed from the damming of the Columbia River at Wallula Gap on the southern Washington border, and covered 4825 square kilometers (3000 sq mi) of the Quincy and Pasco basins and Walla Walla and Yakima River valleys. Downriver, the flood waters ponded again at the entrance to the Columbia Gorge, creating Lake Condon. High-water marks and faint shorelines mark the margins of the lake basins at the 304- to 365-meter (1000- to 1200-ft) contour. The water level at Yakima has been estimated at 61 meters (200 ft) above the present city. Ice-rafted erratic boulders have been found stranded on ridges surrounding the basins (Allen and others 1986, Baker and others 1991). Flood waters, tearing through the channeled scablands, dropped their load of loess, sand, and outwash gravel in the basins. One of the largest flood-related features, the Priest Rapids bar, formed downstream of Sentinel Gap and fills the basin north of Richland.

The lake basins are in the driest areas of the rain shadow of the Cascade Mountains receiving 15.2 to 30.5 centimeters (6 to 12 in) of precipitation per year. Native vegetation consists of the widespread big sagebrush/bluebunch wheatgrass association. These sagebrush areas have been transformed by large irrigation projects that provide Columbia and Yakima River water via pump and canal. The synclinal Kittitas valley has been included in this subregion even though it was not part of glacial Lake Lewis because of its position within the Yakima Folds subregion (10g) and because it has a similar lacustrine history, climate, soil, and land-use capability.

Canyons and Dissected Uplands (fig. 2, 10f; fig. 3, 10f)—In this subregion, the Snake, Grande Ronde, Clearwater, Imnaha, and Salmon Rivers and their tributaries have cut the Plateau to depths of 610 to 1524 meters (2000 to 5000 ft). The canyons penetrate south into Oregon and divide the Blue Mountains from the Rocky Mountains. The dissected portions of the plateau vary from Palouse-like loess hills in the east and south of the Snake River near Dayton or Pomeroy, Washington, to the sharp ridges near the Blue Mountains. In northeastern Oregon, the Grande Ronde River canyon cuts laterally across the area that is recognized as a major source of the lava flows that originally formed the Columbia Plateau (Hooper and Reidel 1989).

Rainfall amounts in the subregion vary from 25.4 to 58.4 centimeters per year (10 to 23 in per yr) depending upon elevation. Native vegetation is diverse due to the proximity of the Blue Mountains and Rocky Mountains and the wide range in precipitation. Pure grasslands without a sagebrush component cover the subregion in its driest portions, the 30.5 to 40.6 centimeters per year (12 to 16 in per yr) precipitation zone. As the Plateau rises toward the Blue Mountains and the northern Rockies, a shrub component, either rose or snowberry, is added to the association.

Grazing and farming has eliminated much of the original plant cover. The sharptailed grouse, once abundant in the fescue-snowberry zone, had disappeared completely (Daubenmire 1970); but it recently has been reintroduced.

Yakima Folds (fig. 2, 10g; fig. 3, 10g)—The Yakima Fold Belt is a series of anticlinal ridges and synclinal valleys that covers 14,000 square kilometers (8700 sq mi) of the western Columbia Plateau (Reidel and Campbell 1989). The folds include the Columbia Hills, the Rattlesnake Hills, Frenchmen Hills, Saddle Mountains, Umtanum, Yakima, and Manastash Ridges. The ridges are composed of layer upon layer of basalt. Oil drilling in the Rattlesnake Hills reached depths of 3648 meters (12,000 ft) without clearing basalt (SCS 1971). The slow deformation of the central Plateau under tectonic influences as well as the immense weight of the flood basalts caused a warping of the western end (Allen and others 1986, Baker and others 1991). The uplift was slow enough to allow the Yakima River to retain its meandering course through the folds.

The Yakima Folds lie in the rain shadow of the Cascade Range. Precipitation amounts vary from 15.3 centimeters at 30.5-meter (6 in at 500-ft) elevation to 38.1 centimeters at 1067.5 meters (15 in at 3500 ft) (SCS 1971). The ridges have steep north-facing slopes. Soil on the north side of the ridges is thin and derived from basalt. Depth to basalt ranges from 30.5 to 50.8 centimeters (12 to 20 in). The gentle south-facing slopes are blanketed with loess to depths of 50.8 to 152.4 centimeters (20 to 60 in). Land-use capability follows this pattern with dryland wheat farming on the south side and grazing on the north side of Rattlesnake and Horse Heaven Hills.

The plant cover of the driest portion of the subregion is the big sage/bluebunch wheatgrass association. It reaches elevations of 820 meters (2690 ft) on the summits of the eastern Yakima Folds. Other associations include fescue/hawkweed in the Columbia Hills near Goldendale and a bitterbrush/fescue community in the east Cascade foothills just below timberline north of Ellensburg and at the eastern end of the Columbia Gorge. Elsewhere the big sage and wheatgrass association occurs right to the forest edge. Daubenmire theorized that the sage/pine ecotone was determined by the change in mean annual precipitation: never more than 36 centimeters (14.5 in) in the sagebrush zone and never less than 40.8 centimeters (16.5 in) in the pine forest (Daubenmire 1956).

The synclinal valleys associated with the Folds, such as the Yakima, Ahtanum, and Kittitas valley, are discussed separately under the Pleistocene Lake Basins subregion.

Palouse Hills (fig. 3, 10h) and Nez Perce Prairie (fig. 3, 10j)—The elliptical Palouse Hills subregion (10h) ranges from Spokane in the north to the edge of the Snake River canyon in the south. The eastern boundary is determined by the transition to the granites of the Rocky Mountains, increased precipitation (up to 55 cm), and the transitional forest soils. The change from the mesic Palouse soil to the drier Walla Walla soil, as interpreted from county soil surveys, marks the western boundary. The loess-covered area southeast of Moscow, Idaho, can be considered the easternmost extension of the Palouse Hills. However, because this area is cut by deep canyons, tributaries to the Snake and Clearwater Rivers, it was included in the Canyons and Dissected Uplands subregion.

Rainfall in the Palouse Hills is in the range of 40.6 to 58.4 centimeters per year (16 to 23 in per yr). Because of the mesic conditions, the soils of the Palouse are classified as Mollisols rather than Aridosols. They have a higher organic matter and clay content than other loessial soils on the Plateau. In spite of the increased precipitation, most of the runoff occurs in January and February, meaning that small, loess-bottomed streams rising within the subregion are intermittent. The only perennial streams originate from the Rocky Mountains to the east.

It has been suggested that the shape of the Palouse hills results from a combination of strong wind action from the southwest that formed sharp dunelike crests toward the northeast and nivation cirques or amphitheaters caused by the accumulation of snowdrifts on the north and east sides (SCS 1980). There is also evidence of the eastward migration of the hill summits during drier times presumably caused by wind action (Baker and others 1991).

The mesic fescue/snowberry plant association marking the transition through the Rocky Mountain foothills has been almost entirely supplanted by wheat farms. Bits of original vegetation survive in the "eyebrows" left where the land is too steep to plow. The Palouse hills are highly productive, producing up to 100 bushels of wheat/acre

(Steiner 1987).

The Nez Perce Prairie (10j) is a rolling loess plain in western Idaho, southeast of the Palouse Hills. Though generally similar to the Palouse region, it differs in having higher elevations overall, colder temperatures, and higher precipitation levels. As a result, the loess soils have a higher clay development. Also, because the Nez Perce Prairie was out of the main path of aerial loess deposition, the soil is shallower than in the Palouse Hills. The Prairie is bounded on all sides by deep river canyons. The area east of Joseph and Enterprise in northeast Oregon is sometimes included with the Nez Perce Prairie (Raisz 1965, SCS 1986, Steiner 1987). However, because of its even thinner loess cover, lower precipitation, and proximity to the Snake River canyon, it has been included with the Canyons and Dissected Uplands subregion.

Deep Loess Foothills (fig. 2, 10i; fig. 3, 10i)—These foothills of the Blue Mountains follow an arc on the northwest slopes beginning just north of Pendleton. The subregion could be a disjunct portion of the Palouse Hills, as it has Palouse soil, the same range in precipitation (40.6 to 58.4 centimeters per year [16 to 23 in per yr]), and similar land-use capability with annual cropping possible. The differences lie in the topography, physiography, and hydrography. The dunelike ridges of the Palouse Hills are replaced by terraced ridges rising to the forested Blue Mountains. The sloping basalt ridges are bisected by perennial streams fed by the higher rainfall and snowpack of the Blue Mountains.

Water Resource Issues of the Columbia Plateau Ecoregion

The initial focus of ecoregion development within EPA was to use ecoregions as a framework to classify streams and to assess water quality. The rationale behind the use of terrestrial landscape characteristics to create water-quality regions was that streams are a reflection of the watersheds which they drain. In moist climatic areas, information on drainage area size, stream discharge, and typical stream substrate is incorporated with the terrestrial landscape data layers to test consistency of ecoregion boundaries with stream types. However, for the semiarid Columbia Plateau, objectives for water-quality assessment did not influence the boundary decisions as much as they would in wetter areas. Traditional use of an ecoregion framework for water quality monitoring and assessment in moist environments carries with it certain assumptions:

1. Perennial streams are used for sampling and setting biocriteria standards.

2. A number of perennial streams within a region ensures a gradient in stream quality.

3. Reference streams are chosen that have their entire length within a particular subregion and are considered representative of that subregion.

4. Small, wadeable streams are used for ease of sampling and to assure that their drainage area lies entirely within a particular ecoregion or subregion.

These assumptions do not apply to a region as arid as the Columbia Plateau.

In the arid and semiarid areas of the Columbia Plateau, most summer precipitation evaporates or is transpired, leaving little water for streamflow. In the driest parts of the Plateau, flow is zero or nearly zero. Almost the entire Plateau, with the exception of the mesic fringes, that is, "meadow steppe," (Daubenmire 1970), has an average yearly runoff of less than 2.5 centimeters per year (1 in per yr). At Esquatzel Coulee, near Connell, Washington, average yearly runoff is estimated at .25 centimeter per year (.10 in per yr) (Nelson 1991). Even in the Palouse Hills subregion, which has the highest precipitation on the Plateau (40.6 to 58.4 centimeters [16 to 23 in]), of all the precipitation that falls, 84 percent is lost to evapotranspiration, 15 percent runs off as surface water, and 1 percent is left and assumed to percolate into the ground (Steiner 1987). Ephemeral streams flow only several days a year or fail to flow at all in particularly dry years. Perennial streams often originate in higher elevations where the source includes snowmelt as well as rain. These "exotic" streams reflect mountain conditions; they are not representative of the lower elevation subregions of the Columbia Plateau through which they flow.

Streams have disappeared as a result of cultivation practices in steep loess hills. Small stream channels may be plowed through and removed from the landscape. Other channels simply fill with soil as it erodes off the hillsides. In the intensively farmed areas, it is impossible to know the original substrate or riparian cover of streams or how many streams once ran perennially. Some larger streams of the arid plateau that do flow are totally appropriated during the irrigation season: water is withdrawn until the streams are dry. Minimum flow regulations that have been established to provide fish and wildlife habitat may be secondary to withdrawal rights and thus are not implemented (Drost and others 1990). In other irrigated areas, the reverse situation may occur; streams that would naturally not be perennial, run with irrigation return water

If the Washington Department of Ecology and the Oregon Department of Environmental Quality are to use the ecoregion framework in the Columbia Plateau, as they have elsewhere, to classify streams, monitor water quality, and eventually set biocriteria standards, adjustments will have to be made to adapt bioassessment to the arid conditions. Possible options are to:

1. Sample only larger systems.

2. Determine the role of springs in the monitoring program.

3. Use reference stream reaches as opposed to reference watersheds.

4. Choose reference reaches of streams within the Columbia Plateau, but with headwaters in neighboring mountainous ecoregions.

5. Model historic conditions.

6. Use reference sites from similar ecoregions.

Additional field work and interdisciplinary discussion are necessary to reexamine water quality monitoring and assessment in this arid region.

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SECTION 2—LEVEL IV ECOREGIONS OF THE BLUE MOUNTAIN ECOREGION OF OREGON, WASHINGTON, AND IDAHO

by Sandra A. Bryce and James M. Omernik

The Blue Mountains of north central Oregon form a transverse bridge between the Northern Rocky Mountains of western Idaho and the Oregon Cascades. The overall structure of the Blue Mountains is a large anticline with a steep north flank in southeastern Washington State, high elevations in the midsection, and gentle south slopes that join the high lava plains of central Oregon (McKee 1972). The wide arc of mountains encompasses three different geologies—a continuation of the Columbia Plateau basalts in the north; a collection of "accreted terranes," that is, ocean crust and volcanic islands that collided with the western end of the continent, in the central part; and more recent rhyolites, andesites, and basalts along the southern perimeter. Individual ranges include the Ochoco, Aldrich, Strawberry, Greenhorn, Elkhorn, Wallowa, and Seven Devils Mountains. Elevations range from less than 275 meters (900 ft) in the canyon depths to nearly 3050 meters (10,000 ft) on the Matterhorn, the highest peak in the Wallowa Mountains.

The ecoregion map presented here (fig. 3) and the report that accompanies it organize the complexity of this region. The explanations below take the reader first through the component landscape characteristics. Then we rearrange and integrate this information in the individual regional descriptions to illustrate the rationale for the boundary decisions. As one might expect, the available information for any region is not evenly distributed. The Blue Mountain area is of great interest to geologists; the available literature is heavily weighted in that discipline. However, we hope the descriptions will illuminate the distinctions between the regions and serve as a reference to those who may use the ecoregion map for any of the applications discussed in the introductory chapter or others not yet invented.

Climate

Water limits ecosystems in the Blue Mountains. It became a limiting factor with the rise of the Cascade Range 20 to 30 million years ago, which formed a barrier to the eastward flow of weather systems off the Pacific Ocean. As a result, the semitropical climate of the area became temperate and continental (Alt and Hyndman 1978). Precipitation is light, and most of it occurs in the winter months; thunderstorms do build occasionally over the higher ranges during the hot, dry summer. In winter, the continental temperature extremes are somewhat reduced because the region is protected from the full brunt of arctic air flow by the northern Rocky Mountains. In the summer, there is enough marine influence over the northern and central Blue Mountains to moderate extremes in heat and drought.

The degree of continentality varies across the Blue Mountains from west to east as well as latitudinally. The Cascade rainshadow extends 233 kilometers (140 mi) to the east to the base of the Elkhorn range. In the rainshadow, light precipitation, high evapotranspiration, and wide temperature fluctuations result in wide expanses of dry forest dominated by ponderosa pine. The xeric conditions and temperature extremes are even greater in the south central Blue Mountains and along the southeastern foothills where the marine influence is entirely blocked.

The continental climate in the northeastern Blue Mountains is masked by a swath of marine air that penetrates eastern Oregon and Washington from the Pacific Ocean. Weather systems flowing through the Columbia River gorge, penetrating the Cascade Range, bring precipitation to the northern Blue Mountain slopes three seasons of the year. Here, increased cloudiness, higher humidity and precipitation foster a productive mesic forest. This wetter, maritime-influenced section is bounded by the Wallowa-Seven Devils Mountains to the east and the Elkhorn range to the south.

The planes of influence delimiting ecosystems in the Blue Mountains are elevational as well as latitudinal. In general, as moisture increases and temperature decreases with elevation, forest productivity improves until heavy snowpack and severe winters shorten growing seasons and limit tree growth at elevations above 1830 meters (6000 ft).

The capabilities of these ecoregions for particular land uses also are determined by moisture availability, growing season, and temperature. Grazing, mining, logging, farming, road building, and irrigation have been practiced in the Blue Mountains for 150 years. Many other authors have traced the history of land-use and management practices that have contributed to the present-day condition of the Blue Mountains ecosystems (Harvey and others 1994, Hessburg and others 1994, Irwin and others 1994, Johnson 1994, Johnson and others 1994, Lehmkuhl and others 1994, McIntosh and others 1994, Oliver and others 1994, Robbins and Wolf 1994, Skovlin 1991). Major land uses and their effects on particular landscape types are discussed in the descriptions of the individual ecoregions.

Geology—The Birth of the Blues

In Devonian to early Jurassic time (275 to 200 myr ago), the Blue Mountains began as a group of offshore islands in the eastern Pacific Ocean. They had formed as island arcs behind subduction zones in the ocean floor. At a subduction zone, an oceanic plate (a piece of earth's crust) slides beneath another plate (oceanic or continental). Intense heat and pressure melt the rocks on the sea floor into magma, which then resurfaces as volcanic eruptions, forming a continental mountain range or a line of volcanic islands. Thick ocean sediments and even an occasional piece of ocean crust may be scraped off and piled against the side of the subduction trench.

At about the same time (geologically speaking), 200 million years ago, the North American continent separated from Europe, carried westward by the widening rift in the floor of the Atlantic Ocean. Oregon's land mass did not exist; the Pacific shore of the continent was then in western Idaho. As the North American continent moved slowly, but inexorably westward, it engulfed a group of offshore islands about 100 million years ago (White and others 1992). Two island groups have been mapped in the Blue Mountains: the Wallowa-Seven Devils terrane and the Olds Ferry terrane near Huntington, Oregon. Remains of limestone coral reefs in the Wallowa Mountains indicate that the islands formed under subtropical conditions in a warm shallow sea (Fifarek and others 1994). The offshore sediments and the erosional material from the islands (shales and fine sandstones) settled between the islands and the mainland as well as between the islands and the subduction trench. These sediments are evident in the Aldrich Mountains (the Izee terrane) and in the Wallowa Mountains (White and others 1992). The island arcs may be remnants of a more extensive system; their rocks are chemically similar to those in arcs accreted to western Canada as well as the Aleutian island chain (Brooks 1979, White and Vallier 1994). Here in the Blue Mountains, the accreted land meets the ancient rocks of the North American plate at the "suture zone," a north-south trench along the western Idaho border, extending from Cascade Reservoir north to Riggins, Idaho (Hooper and Swanson 1990).

The chaotic result of subduction zone geology is represented by the Baker and Grindstone terranes, the formations that form the core of the central Blue Mountains. They are a patchwork of ocean sediments, sandstone and argillite (shaley mudstone), and deep seacrust rocks such as pillow lavas, serpentinite, and gabbro, that escaped the earth's molten maw. Mixed in with these formations are the metasedimentary and metavolcanic rocks metamorphosed in the superheated contact zones near the subduction trench (Brooks 1979, Walker and Robinson 1990, White and others 1992). The complex of sediments, lavas, and ocean crust making up the accreted terranes is aptly called a melange. Melange formations worldwide signal the presence of subduction zones and newly accreted land.

The process of accretion also created reservoirs of magma that recrystallized underground 100 to 130 million years ago to form the granitic core of the Wallowa Mountains, the northern Elkhorn Mountains, and other scattered peaks. The metamorphic areas surrounding these intrusions are the source of gold and other metal deposits that attracted early settlers to the Blue Mountains (Goldstrand 1994, Thayer 1990).

This addition of new land occurred during pre-Cenozoic time. Then about 60 million years ago, during the Tertiary period of the Cenozoic era, intense volcanic activity changed the character of the region yet again. Over a period of 40 million years, the accreted terranes were buried by volcanic material from the chain of volcanoes of the Clarno period, the immense ash falls of the John Day formation, the Strawberry Mountains volcanics, and the Columbia River and Picture Gorge flood basalts. Erosion has since exposed the older pre-Cenozoic rock at higher elevations (Orr and others 1992, Thayer 1990).

The Clarno formation is the remnant of a range of volcanoes, formed during the Eocene period 55 to 35 million years ago, that followed the northeast-southwest axis of the Blue Mountains. The rocks are mostly andesitic, but they include some basaltic and rhyolitic rocks. The volcanic cones mostly have eroded away; scattered remnants may be seen as conical plugs (i.e., White Butte and Black Butte in Wheeler County, Oregon) (Walker and Robinson 1990).

By the time of the John Day ash falls, approximately 35 million years ago, the sea-floor subduction zone had changed to a north-south line rather than the northeast trending Wallowa-Klamath Mountains line (Walker and Robinson 1990). The new location set the stage for the formation of the Cascade range that would eventually block the marine air flow from the interior and change the warm, moist climate of Clarno times to the continental climate of today (Alt and Hyndman 1978).

Between about 17.5 and 6 million years ago, incredible floods of fluid basalt filled what was once an inland sea in Central Oregon and Washington. This Columbia River Basalt group constitutes the entire Columbia Plateau and the northern third of the Blue Mountains. Most of the flows (90 percent) issued from long fissure vents and dike swarms in the northeastern Blue Mountains, except for the Picture Gorge basalt that erupted from vents in the John Day River basin in the central Blue Mountains (Hooper and Swanson 1990).

The northwestward tilting of the Blue Mountains continued throughout this period, partly due to the rise of the subterranean granitic bodies (the Idaho batholith to the east and the smaller granitic bodies under the Wallowas, Elkhorns, and the Nez Perce Plateau) and partly because of regional stresses, faulting, and compression. Faulting defined the major valleys (Grande Ronde, Baker, and Wallowa), and uplifted the adjacent mountain ranges (Wallowas, Elkhorns, and Strawberrys). Since these dramatic geologic happenings, eons of erosion and Pleistocene glaciation have sculpted the peaks and filled the basins with sediments, producing the familiar, seemingly stable, landscape of today.

Blue Mountain Soils

One could imagine that such geological mayhem in the parent material would produce an incredible variety of soil types across the Blue Mountains. And so it does. However, there are zones of moisture, temperature, elevation, and aspect that create a discernible pattern of general soil types across the landscape.

In this moisture limited region, much of the lower elevation soils are xeric or aridic; that is, they are dry for at least 60 to 90 days in the summer months. Early moisture stress effectively shortens the active growing season. In addition, much of the lower elevation, drier soil is derived directly from the geologic parent material. This condition effectively increases the droughtiness of the soil because it is more likely to have rock fragments throughout that reduce the amount of soil available for rooting as well as the water storage capability (Andersen 1956). The coarse fragments do make soil derived from basalt and andesite slightly less erodible than fine-textured soil. In xeric soil regimes, the lack of water limits the development of soil organic content and slows soil weathering. Productivity is dependent upon a thin surficial organic layer or upon regular fires to release nutrients accumulated in woody debris and dried grasses

(Harvey and others 1994). Thus, when moisture is limiting, a number of factors contribute to a less productive medium for plant growth

The geologic parent material for soils are the rhyolites and tuffs in the southern Blue Mountains, mixed volcanic debris and ash in the John Day/Clarno region, sedimentary material in the Aldrich and Elkhorn Mountains, and andesite and basalts in the Strawberry Mountains. Mixed with these are the droughty soils of the granitic and metamorphic inclusions Xeric conditions and characteristic plant cover persist into higher elevations on south-facing slopes and on metamorphic parent material.

At higher elevations, above about 762 meters (2500 ft) in the north and 1525 meters (5000 ft) in the south, conditions tend to become cooler and moister and so also more productive. Soil at these elevations is normally udic or moist. In the udic moisture regime, there are fewer than 45 days of dryness in the 120 days following June 20. The temperature regime is either frigid or, in the higher elevations above 1525 meters (5000 ft), cryic.

The most productive soils of the Blue Mountains are those composed of fine materials that have been aerially deposited. Ash deposits from the eruptions of Glacier Peak and Mount Mazama (12,000 and 6,600 yr ago, respectively) are as much as 1-meter thick in the mid- to high-elevation forested areas. Much of the ash has eroded away in the lower elevation grasslands and on south-facing slopes, but it has been preserved in more mesic zones, such as north slopes and sites having had a continuous forest cover. The fine silt loam ash soils have a high water holding capacity, a high water infiltration rate, and a largely rock free growing medium. Again, most of the nutrients are near the surface. Without a vegetative cover, ash soils are very vulnerable to erosion and subsequent loss of productivity (Harvey and others 1994). In general, the major areas of ashy soil correspond with the regions of Mesic Forest (fig. 4, 11l), especially in the central and northern Blue Mountains.

Aeolian loess (glacial silt deposited by wind during the Pleistocene) is also a significant addition to Blue Mountain soils, particularly in the northern Blue Mountains adjacent to the Columbia Plateau (see section 1 above). Like ash, loess deposits can ameliorate the droughtiness of the soil. Loess soils also are fine-textured, rock free, and high in nutrients.

Blue Mountain Vegetation

As we walk the landscape and view the patterns of vegetation at that scale, we notice the variability in plant associations, responding to variations in disturbance, microclimate, aspect, and local topography. Various species (table 2) dominate over time as conditions change. How can we generalize about such diversity?

We can compare this conundrum with the phenomenon that happens upon inspection of a pointillist painting, e.g., the *Isle du Gran Jatte* by Seurat. From the vantage point of a few inches away from the canvas, we see only a dizzying array of many-colored dots. But if we step back away from the painting, the dots fuse to reveal pattern. Similarly, if we conceptually back away far enough from the landscape, the confusing collection of plant associations in the Blue Mountains do disclose a pattern, dependent upon temperature, elevation, growing season, soil type, and depth.

The most apparent pattern in the area is a progression of vegetation types with increasing elevation, beginning with grasslands at the lowest elevations and changing to shrublands, ponderosa pine woodlands, true fir mesic forest, subalpine forest and parkland, and alpine meadows as elevation increases. Tying these patterns to a map is a more difficult prospect. However, guided by elevation, parent material, soil type, fire regime, and historic vegetation patterns, we have created a model that includes vegetation as one element in the integration of landscape characteristics that compose a map of ecosystems.

In the lowest elevations, grassland communities prevail in the areas of xeric and aridic soils. They range from bluebunch wheatgrass-Sandberg's bluegrass associations in the warmest, driest canyons to Idaho fescue associations in deeper, moister soils. Shrublands and juniper/grassland savannah form the transition from grassland to forested slopes. Along the southern foothills, bitterbrush, mountain-mahogany, and sagebrush mix with juniper to provide cover, browse, and berries for birds, elk, and deer (Johnson and Clausnitzer 1992). In the north-central and northern Blue Mountains, sagebrush and western juniper are replaced by a mesic shrub assemblage—ninebark, common snowberry, serviceberry, Rocky Mountain maple, and oceanspray.

Ponderosa pine grows in a very wide range across much of the Blue Mountains as a climax species in the warmest and driest forested areas and as a seral dominant in areas of frequent fire (Harvey and others 1994, Hessburg and others 1994). As a seral dominant, it grows at the moister end of the xeric soil regime where grand fir is technically the climax species. However, here the grand fir is at the extreme end of its range. It is susceptible to fire, moisture-stressed, and prone to disease and insect infestations (Hessburg and others 1994, Johnson and others 1994). Under a normal fire regime, with a fire frequency as short as 10 years, the ponderosa pine persists while the grand fir seedlings continually succumb to fire except near springs or other moist refugia.

Historically, the forest types were rather sharply bounded by elevation. Ponderosa pine dominated the xeric soil regions, the fire-prone areas, while true fir associations, the mesic forest, dominated higher elevations. The mesic forest zone historically began at about 762 meters (2500 ft) in the north and 1500 meters (4900 ft) in the southern mountains.

Before widespread fire suppression, these mesic forests had a low fire frequency of 50 to 300 years or more; but the fires were hot, intense, and extensive. Lodgepole pine and western larch, the seral species at the higher elevations of 1220 to 2285 meters (4000 to 7500 ft), revegetated the burns to create a patchy forest landscape. Insect and disease infestations cycled within the limited area of susceptible true fir forest, but infestations did not often reach epidemic proportions (Hessburg and others 1994).

Fire suppression has blurred the historical-elevational zonation of forest vegetation. Present day vegetation patterns do not give us a clear picture of the natural affinities of forest plant associations. Because of 60 years of fire suppression, Douglas-fir, grand fir, and Engelmann spruce have expanded their range to lower elevations beyond their normal mesic locations. During this same period, old-growth stands of ponderosa pine and western larch have been cut, leaving thickets of late successional fir forest. With the increase in acreage of overstocked mesic forest, insects and disease have become more common. Over the years, the proportion of forest land in the Blue Mountains dominated by ponderosa pine has declined on all ownerships from 80 percent in 1936 to 25 percent in 1992 (Hessburg and others 1994).

In the new atmosphere of ecosystem management, proposed management strategies include uneven-aged management of multiple tree species, reduction of grazing densities, restoration of understory shrub communities (Irwin and others 1994), and prescribed burning to emulate the historic fire regimes and to reestablish the seral forest (Oliver and others 1994). A map like the ecoregion map presented here (fig. 3), developed as a model of a time when there were minimal human impacts on the landscape, can serve to guide restoration efforts by suggesting a more "natural" distribution of vegetation. With that goal in mind, the ecoregions delineated here reflect the time when ponderosa pine in park-like stands dominated both the lower elevation sites and the xeric grand fir and Douglas-fir series sites as well.

There is some discussion about exactly how much of the presettlement vegetation pattern was due to Native American "prescribed burning" (Robbins and Wolf 1994). Could the park-like stands of ponderosa pine have been "managed" by early Native Americans? Perhaps early man and the forest community have coevolved since the Pleistocene. There is evidence to indicate that the forest has evolved under a fire regime, whether human-caused or not, and that it maintained itself in a healthier condition than today (Harvey and others 1994, Hessburg and others 1994, Johnson 1994, Lehmkuhl and others 1994, Robbins and Wolf 1994).

The historic view of an area may provide guidance to restoration efforts by serving as a model or ideal goal. Though we may never reach the ultimate goal (the presettlement condition), what is attainable will be somewhere between the degraded condition and the historic condition. How closely we approach the goal depends upon social values and the availability of funding.

In summary, the climate, geology, soil, historic and present day vegetation, and important influences on these factors (e.g., the fire regime) were the major categories of information that contributed to the regional delineations for this project. Map analysis, consultation with regional experts in meetings and over the phone, and literature review were all integrated to create the map of Level IV ecoregions of the Blue Mountain ecoregion of Oregon and Washington. The following regional descriptions indicate the rationale behind specific boundary decisions.

Descriptions of the Blue Mountains Subregions

Composite subregions—To limit the number of subregions and to strive for cartographic simplicity, a number of disjunct subregions that are the result of elevational factors have been combined into two composite subregions, the Mesic Forest (fig. 3, 11l) and the Subalpine Areas (fig. 3, 11m). Thus, there is just one subalpine subregion instead of three (Wallowas subalpine, Elkhorns subalpine, and Strawberry Mountains subalpine), graphically displayed as disjunct areas of the same color. The scattered portions of each composite subregion have a general similarity across the Blue Mountains ecoregion. However, there is some latitudinal variability among the disjunct areas. The Mesic Forest and Subalpine Subregions are described in general below, and each individual area (e.g., Wallowas subalpine) is then described in more detail in its appropriate subregional description.

Subalpine Areas (fig. 2, 11m; fig. 3, 11m)—The widest expanses of Subalpine Areas (fig. 3, 11m) appear in the high Wallowa, Elkhorn, Greenhorn, and Strawberry Mountains. Elevations at which the subalpine forest becomes broken by high meadows and parkland vary from north to south. Subalpine parkland, i.e., the mosaic of forest patches and meadows, begins at approximately 1830 meters (6000 ft) in the northern Blue Mountains and at 2130 meters (7000 ft) in the south central Blue Mountains. The high elevation forests and meadows share a cold climate, cold, often shallow, soils, short growing season (10 to 70 days), heavy snowpack, and high annual precipitation (85 to 150 cm).

The subalpine lithology varies from Columbia River basalt in the northern Blue Mountains to granitics in the Wallowas, granodiorites in the Elkhorns and Greenhorns, and ultramafics and andesites in the Strawberry Mountains. Subalpine fir, and its seral partners, lodgepole pine, western larch, and Engelmann spruce, reach their highest potential on silt loam soils derived from volcanic ash and loamy sands from pumice and ash. Lodgepole pine prefers ashy soil on gentle ridges with slopes less than 15 percent. Western larch can grow in steeper areas, where deeper colluvial soils provide more stored moisture (Johnson and Simon 1987). In more extreme locations to 2440 meters (8000 ft), whitebark pine, also seral to subalpine fir at lower elevations, becomes co-dominant.

Mesic Forest Zone (fig. 2, 11l; fig. 3, 11l)—The Mesic Forest Zone (fig. 3, 11l) appears throughout the Blue Mountains in areas of low moisture stress. The largest expanses are in the north where marine air flowing through the Columbia River Gorge brings high rainfall amounts. Elsewhere, in the central and southern Blue Mountains, elevation increasingly influences the distribution of mesic forest. As the climate becomes more continental, only higher elevations capture the amount of precipitation necessary to support the mixed conifer and fir forests. Mesic forests have a high affinity for ash-derived soils with high moisture-holding capacity, which retard the onset of summer drought in mountainous areas with cooler temperatures. The mesic forest starts at about 915 meters (3000 ft) in the north; farther south and west, the true fir forest is limited to areas above 1830 meters (6000 ft) or to northern aspects.

The subregion map (fig. 3) depicts the Mesic Forest Zone as it might be under a more "natural" fire regime. The early map by Andrews and Cowlin (1936) for the forest types of the U.S. Department of Agriculture's Forest Service served as a model for the delineations of mesic and xeric forest on the subregion map. This 1936 map provides a snapshot of forest distributions before fire suppression and widespread high grade logging had changed the sharp elevational patterns of the eastside forest. As a result, the mesic forest delineated on the subregion map (fig. 3) is an expression of the higher, moister end of the grand fir series. Areas where grand fir is technically the climax species, but where it would not normally reach maturity because of frequent fires, appear as xeric forest on the subregion map. Thus, the mapped zones of xeric and mesic forest do not match the full range of the true fir forest associations, but they do correspond more closely to the xeric and udic soil temperature regimes.

Subregions in the Cascade Rainshadow—As the Cascade Mountains began to block the flow of moist Pacific air to what is now central Oregon 20 to 30 million years ago, the warm, tropical climate of the Eocene epoch gave way to a drier, cooler, continental climate. The areas identified on the map as the John Day/Clarno Uplands (fig. 3, 11a) and the John Day/Clarno Highlands (fig. 3, 11b) constitute two elevational divisions of subregions in the Cascades rainshadow.

John Day/Clarno Uplands (fig. 2, 11a; fig. 3, 11a)—The John Day/Clarno Uplands (fig. 3, 11a) subregion takes its name from two geologic formations that appear in several subregions of the Blue Mountains; however, their greatest extent and most distinctive expression occur within the boundaries of this subregion. The John Day/Clarno Uplands are a ring of dry foothills that surrounds the western perimeter of the Blue Mountains and separates the north-central Blue Mountains from the Southern Blue and Ochoco Mountains. The "John Day Country" is a rough sea of highly dissected hills, palisades, and colorful ash beds dotted with junipers and cut by the valleys of the John Day and Crooked Rivers. Elevations range from 457 to 1525 meters (1500 to 5000 ft). Precipitation falls as spring and fall rains and light snow in the winter. Annual precipitation varies with elevation, from 23 centimeters (9 in) at lower elevations to 40 centimeters (16 in) at higher elevations.

The Clarno formation of 54 to 37 million years ago (Eocene and lower Oligocene periods) began as a pre-Cascades chain of andesitic volcanic cones erupting along the northeast trending axis of the Blue Mountains. The location of the Clarno volcanoes indicates the past presence of a parallel subduction zone offshore (Walker and Robinson 1990). The Clarno formation today comprises a wide variety of eroded remnants of the mountain chain: andesites, basalts, tuffs, breccias, and colorful cliffs of petrified mudflow (lahars). Red paleosols (fossil forest soils) and fossilized leaves and nuts give evidence of the tropical climate of the time (Retallack 1991).

By the time of the John Day formation, 37 to 22 million years ago (Oligocene to early

Miocene periods), the ocean floor subduction zone had shifted to the west and taken up a north-south position west of the rising Cascade range. Several thousand feet of airborne and waterborne tuffs and ash filled a topographic basin between the western Cascades and the now-extinct Clarno volcanic chain. The ash flows and airfall tuffs are assumed to have come from several sources east of the Cascades (Thayer 1990, Robinson and others 1990). Robinson and others (1990) give us a startling realization of the immensity of geologic time by relating that the lower unit of the three strata of John Day ash (350-m deep) spans a period of 12 million years of deposition at a rate of about 28 mm/1000 year. These formations of red, green, and grey ash are softer and more easily eroded than the surrounding basalt, and thus, form valleys or bowl-like depressions. The ashy beds weather to a fine clay. The fossilized remains of a diverse mammalian fauna have been preserved in the John Day Fossil Beds National Monument near Picture Gorge, Oregon (Thayer 1990).

Outside of the John Day ash beds, the soils are more varied, reflecting the variety of volcanic parent materials in the region. The soils are generally deep to bedrock with a very stony loam surface layer and a clay loam or clay subsoil. The soils at lower elevations have an aridic soil moisture regime with average annual precipitation amounts of less than 30 centimeters (12 in). They include Aridic Palexerolls, Chromic Haploxererts, Xeric Paleargids, Aridic Haploxerolls, and Aridic and Lithic Argixerolls. The soils at higher elevations have a xeric moisture regime with annual precipitation amounts of 35 centimeters (about 14 in). These soils include Lithic Argixerolls, Calcic Pachic Argixerolls, and Pachic Palexerolls. Soils derived directly from basalt differ in that they are shallow to moderately deep, with a surface layer of very cobbly loam and a very cobbly clay-loam subsoil. Basaltic soils include Lithic Argixerolls and Aridic Argixerolls.

The potential natural vegetation of the John Day/Clarno region consists of grassland and grassland savannah. Bluebunch wheatgrass, Idaho fescue, and Sandberg's bluegrass with big sagebrush and bitterbrush cover the lower elevation, drier areas. Juniper woodland forms the transition zone between the dry grasslands and the ponderosa pine forests of the higher elevations. The juniper zone has an elevation range between 760 to 1400 meters (2483 to 4593 ft) where the rainfall is between 20 and 30 centimeters (8 to 12 in).

Juniper woodland and savannah have increased markedly over the last 50 years. The expansion can be traced through historic photographs. The change in spatial extent is also apparent when comparing a forest type map of the 1930s with a present-day vegetation map (Andrews and Cowlin 1936, Kagan and Caicco 1992). Though it is theorized that a combination of fire suppression and cattle grazing caused the most recent advance in juniper distribution, the fossil record does show regular expansion and contraction of juniper distribution over the last 5000 years. Increased moisture and fewer, low intensity fires favored juniper, while drought and increased fire suppressed it (Johnson and others 1994). Juniper has an affinity for the clay soils of the region; it benefits from the relatively high moisture-retaining capacity of clays (Johnson and Simon 1987).

The southern edge of the Columbia River basalt marks the northern boundary of the John Day/Clarno Uplands (fig. 3, 11a). The boundary is quite clear near Antelope, Oregon, where the basalt flows of the Plateau crop out in a prominent rim called the Antelope Scarp. Further east, on Highway 19 between Fossil, Oregon, and Mayville, Oregon, one can drive 7 miles up a steep grade to the level of the Columbia Plateau. The change from John Day country to the rolling Columbia Plateau is sharp enough here to be a "line drawn on the ground." The southwestern boundaries of the John Day/Clarno subregion end on the juniper flats of the Deschutes River basin. The transition from the John Day/Clarno Uplands (fig. 3, 11a) to the Continental Zone Foothills (fig. 3, 11i) subregion is a combination of a change in geology and climate. In the Continental Zone Foothills (fig. 3, 11i), the regional aspect is more southerly, the climate more continental, and the underlying geology changes from John Day and Clarno deposits to more recent volcanics and tuffs.

John Day/Clarno Highlands (fig. 2, llb; fig. 3, 11b)—The change from juniper and grassland savannah to ponderosa pine woodland marks the boundary between the John Day/Clarno Uplands (fig. 3, 11a) and the forested John Day/Clarno Highlands (fig. 3, 11b). The final arbiter of the juniper/pine boundary was again the forest-types map of Andrews and Cowlin (1936). It was completed when juniper distribution was much less extensive than today. The elevation of the change from grassland to pine woodland varies from 762 meters (2500 ft) in the north, to 1525 meters (5000 ft) along the southern margin of the Ochocos, and 1400 to 1463 meters (4600 to 4800 ft) in the interior John Day valley. The "fuzzy boundary" or transition area between these two regions estimates the extent of a juniper/pine mixed woodland (fig. 4).

The John Day/Clarno Highlands span a territory with the same east-west extent as the John Day/Clarno subregion but at a higher elevational range. This subregion is bounded by the eastward extent of the rainshadow of the higher peaks of the Cascade Mountain range. As a result of the mountainous barrier to marine weather systems, the region exhibits a continental climate regime: little rain with wide extremes in annual and daily temperatures. However, the continental climate in this area is moderated by a bit of marine influence spreading southward from the Columbia Gorge and westward through the low passes of the Cascades. The John Day/Clarno Highlands subregion is not as dry, nor are the temperature extremes as great, as they are in the Continental Zone subregion of the southern Blue Mountains and the Continental Zone Foothills to the south and east (Loy and others 1991).

The soil moisture regime in this subregion is xeric, meaning that the soils are continuously dry for 60 to 90 days during the summer months. The soil temperature regime is frigid. In the 6600 years since the deposition of the Mount Mazama ash layer, erosion has had a greater impact on these dry mountains of moderate elevation. With the ash layer eroded away and no appreciable loess deposits, the water-holding capacity of the soil is limited. Representative soils have a surface layer rich in organic matter, with or without a clay-enriched subsoil. They are Ultic Argixerolls, Ultic Palexerolls, and Lithic Ultic Haploxerolls.

The entire subregion is characterized by a predominance of ponderosa pine forest as a potential vegetation cover. In the past, frequent low-intensity fires kept mesic forest to a minimum distribution. Before fire suppression, true fir forests grew to maturity only in moist areas that experienced few fires. As a result, seral ponderosa pine, and to a lesser degree lodgepole pine and Douglas-fir, dominated the forest of this subregion early in this century. The trees grew in park-like stands, at a low enough density to avoid excessive moisture stress. Shade-tolerant young growth of true fir regenerated in the understory but did not survive the fires that recurred every 10 to 15 years (Hessburg and others 1994). Understory vegetation includes bitterbrush, mountain mahogany, bluebunch wheatgrass, pinegrass, and elk sedge.

The early forest type map (Andrews and Cowlin 1936) shows little late-successional Mesic Forest (fig. 3, 11l) in the John Day/Clarno Highlands subregion compared to other subregions of the Blue Mountains. Only the Continental Zone of the south central Blue Mountains has less true fir forest mapped. Along the spine of the Ochoco Mountains, those peaks over 1830 meters (6000 ft), e.g., Wolf Mountain, Peterson Point, and Mount Pisgah, have a true fir mantle. True fir also grows on the north slopes of these and other major Ochoco peaks and near major springs between 1525 and 1830 meters (5000 and 6000 ft). The north slopes are a repository of Mazama ash that provides the optimum growing medium for the grand fir.

Dry ponderosa pine forest and grassland penetrate almost 30 kilometers (50 mi) east along the John Day River valley from Picture Gorge to Prairie City, Oregon. There the

John Day/Clarno formations and the Picture Gorge basalts meet the melange geologic region, a chaotic collection of ocean sediments, deep sea crust, granitic intrusions, and metamorphosed sediments and basalts, that constitute the core of the central Blue Mountains. The change in geology plus a pronounced increase in elevation at the Strawberry, Greenhorn, and Elkhorn Mountains mark the eastern boundary of the John Day/Clarno Highlands subregion where orographic uplift of weather systems and expansive high elevation areas produce a significant extent of mesic forest and subalpine parkland. Farther north the John Day/Clarno Highlands subregion meets the Maritime-Influenced Zone of the northern Blue Mountains.

Maritime-Influenced Zone (fig. 2, 11c; fig. 3, 11c)—The Maritime-Influenced Zone (fig. 3, 11c) is that part of the Blue Mountains that directly intercepts the marine weather systems moving east through the break in the Cascade mountain range at the Columbia River Gorge. The wet weather is intensified as the clouds rise up the slopes of the northern Blue Mountains; rain and snow is delivered to these mountains three seasons of the year. The maritime area receives more precipitation than anywhere else in the Blue Mountains except the high Wallowas and Elkhorns (Loy and others 1991).

This ecological subregion is a mountainous continuation of the drier Columbia Plateau to the north; it is composed of a lower elevation xeric forest surrounding large areas of higher elevation mesic forest and a small area of subalpine parkland in the Blue Mountains of southeastern Washington and in the northern Elkhorn Mountains.

Geologically, this zone is composed almost entirely of Columbia River basalts, except for a bit of John Day and Clarno deposits in the far west and south. The uplifted basalt plateau has an elevation range of 915 to 2135 meters (3000 to 7000 ft). Mean annual precipitation varies from 58 centimeters (23 in) at the grassland-pine margin to 100 centimeters (40 in) in the upper elevations of the upper Grande Ronde basin to the south.

The soil of the region, however, is not a direct reflection of its basaltic parent material. Much of northeast Oregon is covered by an ash mantle as much as 1-meter thick from the eruption of Mount Mazama in southwestern Oregon 6600 years ago. Glacier Peak and Mt. St. Helens also contributed ash layers 12,000 and 10,000 years ago. Elsewhere in the Blue Mountains, in grassland areas and south-facing slopes, much of this ash layer has eroded away; but this area, because of its adequate moisture, has had a constant vegetative cover and low fire incidence that preserved the ash layer.

Because of the region's proximity to the Columbia Plateau, there is also a considerable amount of loess soil present, particularly in the lower elevation xeric forest and on the north slopes of the northern Blue Mountains. Loess soil also has an increased water holding capacity, though not as great as ashy soil. Loess soil's high nutrients, rock-free texture, and moist microclimate mean high productivity for the Idaho fescue and mesic shrub associations (Johnson and Simon 1987). Douglas-fir also grows abundantly on loessial soil. It is normally at a competitive disadvantage with ponderosa pine on soils with little or no loess influence, but on loess soils

Douglas-fir is able to compete successfully (Johnson and Simon 1987).

In the ponderosa pine woodland at the grassland-forest transition and in the adjoining lower elevation forest, the soil moisture regime is xeric. The soils, Ultic Argixerolls, Ultic Palexerolls, and Lithic Ultic Haploxerolls, have a surface layer rich in organic matter with or without a clay enriched subsoil. Because of the increased moisture availability in the subregion generally, these xeric forests occur at a lower elevation than elsewhere in the Blue Mountains. Ponderosa pine and bunchgrass associations occur on south aspects at about 640 meters (2100 ft) and pine/snowberry at 730 meters (2400 ft). In canyons and in the forest understory, ninebark, serviceberry, oceanspray, and snowberry constitute a diverse shrub community that is able to regenerate after fire. Tree regeneration is sometimes delayed in the dense shrub layer (Johnson and Clausnitzer 1992). However, once established, Douglas-fir is resistant to the constant movement of colluvial soils at canyon sites. The steep canyon slopes at elevations of 700 to 1770 meters (2300 to 5800 ft) in this subregion are covered with stands of Douglas-fir on soils formed in ash, loess, and basalt colluvium (Pachic Ultic Haploxerolls and Vitrandic Argixerolls).

Mesic Forest Section (fig. 3, 11l)—Above about 762 meters (2500 ft), in the Mesic Forest (fig. 3, 11l) section of the Maritime-Influenced ecoregion, the soil temperature regime is still frigid, but the soil moisture regime becomes more udic (moist). At the upper elevations of the mesic forest section, where moisture continues to increase, the soil temperature regime becomes colder, in the cryic range. At mid- and high elevations in this region, the soil surface is composed of a thick mantle of volcanic ash, particularly on north-facing slopes. These ashy soils may have a clay-enriched subsoil (Alfic Udivitrands and Andic Eutroboralfs). Those without a clay subsoil are called Typic Udivitrands. Soils on south-facing slopes, with more of the volcanic ash eroded away, may be drier for a longer period of time. They are the Typic Vitrixerands and Vitrandic Xerochrepts. Those soils with a clay-enriched subsoil are called Vitrandic Haploxeralfs, and those with a dark surface layer rich in organic matter are Vitrandic Haploxerolls.

Grand fir, Douglas-fir, lodgepole pine, Engelmann spruce, larch, and subalpine fir all grow within the moisture and temperature ranges of the Mesic Forest Zone. Because of the relative lack of moisture stress and the nutrient value of the ash soil, forest productivity in the Maritime-Influenced Zone is higher than in other ecoregions of the Blue Mountains. Larch, Douglas-fir, and lodgepole pine are the seral species; historically, seral stands covered large areas at these elevations after wildfire. In the late-seral grand fir forests, understory species range from twinflower and birchleaf spirea in the drier end of the grand fir series at elevations as low as 762 meters (2500 ft), to Rocky Mountain maple or Pacific yew in the wettest areas, with big huckleberry and grouse huckleberry associated on the highest, coldest sites (Johnson and Clausnitzer 1992).

Subalpine Areas (fig. 3, 11m)—The Subalpine Areas (fig. 3, 11m) in the Maritime-Influenced Zone are limited to an area at the northern end of the Elkhorn range and scattered areas of subalpine fir and ridgebrow grasslands in the Blue Mountains of southeastern Washington, particularly near Table Rock lookout. Johnson and Clausnitzer (1992) list the elevation of subalpine fir in the north as 1400 to 1705 meters (4600 to 5600 ft). At its lower elevational limits, subalpine fir is a component of the closed canopy mesic forest. It is difficult to find and map the point at which this forest cover becomes patchy and interspersed with alpine meadows. As a result, subalpine areas could be shown more extensively in the northern Blue Mountains, but most likely the areas are too fragmented to be depicted on a map of this scale.

The boundary decisions for this subregion depend upon tracking the limits of the marine influence coming through the Columbia River Gorge from the west. The marine influence is evident first at Madison Butte and Tupper Butte in south central Morrow County, Oregon, with the appearance of areas of mesic fir forest. To the west, the crest of the ridge is several hundred feet lower, just above 1524 meters (5000 ft), and the areas of climax grand fir forest disappear (Andrews and Cowlin 1936). This is the point at which we pass out of the path of weather systems moving east through the Columbia Gorge and into the shadow of the Cascade Mountains. From here east the northern boundary of this subregion is marked by the transition from Columbia Plateau grassland to the moister higher elevation ponderosa pine woodland of the Blue Mountains. To the south and west, the boundary between the Maritime-Influenced Zone and the John Day/Clarno Highlands follows the convex slope of the anticline of the northern Blue Mountains as it drops into the dry south-facing canyon slopes of the North Fork of the John Day River. Farther south and east the boundary closely follows to the ridgeline above the headwaters of the upper Grande Ronde River. Though the marine influence would overlap the crest of the ridge to the south, the geology also changes in this vicinity, from Columbia River basalts to the much more complex geology of the central Blue Mountains, the Melange Subregion.

Melange Subregion (fig. 2, 11d; fig. 3, 11d)—The Melange (11d) subregion forms the central core of the Blue Mountains. Webster's Dictionary defines *melange* as a "mixture of heterogeneous and often incongruous elements." These are perfect adjectives to describe the collection of limestone, marine mudstones, serpentinite and peridotite, and the metamorphic greenstones and schists that make up the Elkhorn, Greenhorn, Vinegar, and Aldrich Mountains.

Just as incongruous was the way in which these formations became a part of Oregon's land mass 100 million years ago. They are "accreted terranes," i.e., chains of volcanic islands that collided with the continental margin or portions of dismembered oceanic crust that were scraped off by the conveyor-belt movement of an oceanic plate diving beneath the continental crust at a subduction zone. In the central Blue Mountains Melange subregion, a large piece of oceanic crust, an ophiolite succession, composed of serpentine and peridotite, gabbro, dikes, pillow lavas, and deep sea sediments (in that order!), constitutes Canyon Mountain above John Day, Oregon (Hamblin 1985, Thayer 1990).

The soils over serpentine and other metamorphic rocks in the Blue Mountains can be thin and rocky, particularly in erosional settings. They do not retain moisture, and they create a hostile environment for plant growth, in part because of their high magnesium content. Streams draining metamorphic areas dry up early in the season, and xeric plant associations persist to higher elevations in metamorphic areas.

After their collision with the continental margin, the new lands were partially submerged by the accumulation of muds and sediments in Cretaceous seas. The sedimentary rocks in the Aldrich Mountains, rising south of John Day and Dayville, Oregon, are composed of thick deposits of shales and very fine sandstones (graywackes) that accumulated to great depths in the ancient sea. They are more crumbly and slightly more erodible than the argillites of the Elkhorn Mountains (Walker and Robinson 1990). The soil from the graywackes is a well-drained gravelly loam soil (Lithic Xerochrept) that supports ponderosa pine with fescue and Sandberg bluegrass.

Scattered granitic bodies of Jurassic to Cretaceous age, about 90 to 140 million years ago, have intruded the matrix of accreted terrane in the Melange Subregion. Granite intrusions have been exposed at Dixie Butte, Vinegar Hill, and the central and northern Elkhorns. Gold and silver were discovered in the margins of the granitic intrusions, and other precious metals have been mined from the metamorphic areas. Placer mining altered the structure of many of the streams in the region. The town of John Day is built upon the tailings piles of a mining operation (Thayer 1990).

Above the older Paleozoic and Mesozoic formations in the central Blue Mountains are several thousand feet of ash and lava from widespread post-Cenozoic volcanism, e.g., the Clarno, John Day, Picture Gorge, and Strawberry Mountain volcanics. Beginning about 15 million years ago, these ranges, the Aldrich and Strawberry Mountains and ridges to the north, were compressed from both the north and the south and uplifted along the John Day fault to form the folded topography evident today (Thayer 1990, Walker 1990a).

By the end of the Pliocene period, only the highest peaks of the original accreted terranes protruded through the various basalt and erosional layers; the early rocks of the accreted terranes today constitute 10 to 15 percent of the mountainous area of the Blue Mountains (Walker 1990a). Glacial activity during the Pleistocene then sculpted the major peaks into cirques and amphitheaters, shaped valleys above 1525 meters (5000 ft), and left major sedimentary deposits in valley bottoms (Thayer 1990).

At the lowest forested elevations 1372.5 to 1525 meters (4500 to 5000 ft) in the Melange Subregion (Map Unit 11d), ponderosa pine and juniper grow in an open forest above a diverse shrub understory of mountain mahogany, bitterbrush, and squaw currant. In higher, cooler sites, Douglas-fir is co-dominant with ponderosa pine with the same understory plants. At the highest elevational ranges for Douglas-fir, on dry slopes and ridgetops approaching 1677.5 meters (5500 ft), a Douglas-fir/pinegrass or Douglas-fir snowberry association may be found. Recurring fire favors the persistence of ponderosa pine with a pinegrass or elk sedge understory (Johnson and

Clausnitzer 1992). All of these associations are adapted to grow on metamorphic substrate; the droughtiness of the soil may be ameliorated by a thin mantle of ash or loess.

The eastern Strawberry Mountains differ from the older accreted terranes of the Melange subregion in that they are composed of mostly younger basalt and andesites. The residual soil from the basalt and andesite substrate differ from ash and loessial soil in that they have a finer texture in the upper profile, coarser fragments in the soil matrix, and a lower moisture-holding capacity, resulting in a wider elevational range of ponderosa pine and Douglas-fir dominated forest. Where an ash layer is present, the productivity of the soil increases and grand fir is able to grow. The soils in this zone have a frigid temperature regime and a xeric moisture regime. The mixed forest soils, with or without an ash layer or a clay-enriched subsoil, include Typic and Alfic Vitrixerands, Vitrandic and Ultic Haploxeralfs, and Vitrandic and Dystric Xerochrepts. Under the more xeric, ponderosa pine forest in the lower elevations, soils form from basalt residuum and colluvium and have a surface layer high in organic matter; they may or may not have a clayey subsoil (Vitrandic, Lithic and Lithic Ultic Haploxerolls, Lithic and Typic Argixerolls).

Mesic Forest Section (fig. 3, 11l)—In the Elkhorn Mountains, at elevations surrounding the subalpine and alpine core, the Mesic Forest section here (fig. 3, 11l) resembles that of the Maritime-Influenced Subregion (fig. 3, 11c) to the north. The difference is that the area is outside of the direct influence of the marine weather.

However, these mountains receive adequate precipitation to support a true fir forest community (up to 85 cm [35 in]) because of orographic uplift on the west slopes above the John Day basin. The soil-moisture regime here is drier than in the maritime-influenced area, but the onset of moisture stress is delayed by a moisture-retaining ash mantle. Characteristic soils in this Mesic Forest section (fig. 3, 11l) are Typic and Alfic Vitrixerands, Vitrandic and Ultic Haploxeralfs, and Vitrandic and Dystric Xerochrepts.

Subalpine Areas (fig. 3, 11m)—At elevations above 1585 meters (5200 ft) in the Elkhorns and about 1700 meters (5600 ft) in the Strawberry Mountains, a subalpine forest of subalpine fir, lodgepole pine, and Engelmann spruce grades into whitebark pine and alpine sagebrush openings, and finally into alpine meadows at about 2285 meters (7500 ft) (fig. 3, 11m). Soils with a thick ash mantle are classified as Typic Vitricryands, with a thin ash mantle, Andic Cryumbrepts, and with a thin ash mantle and a clay-enriched subsoil, Andic Cryoboralfs. These soils are cryic and udic (moist). In alpine meadows, the soils may be shallow, Lithic Cryumbrepts and Cryochrepts, or moderately deep with a thin ash mantle and an organic-matter rich surface (Andic and Vitrandic Cryumbrepts).

Wallowas/Seven Devils Subregion (fig. 2, 11e; fig. 3, 11e)—The Wallowas/Seven Devils range began as a volcanic island arc in a warm, low latitude sea. As the North American continent was set in motion westward by the widening of the mid-Atlantic rift 200 million years ago, a subduction zone developed at the western edge of the continent in what is now western Idaho. As the North American plate moved westward, it collided with and overran the complex island arc system to form the earliest Oregon land mass. Geologists have pieced together the evidence of this genesis from the collage of ocean sediments, limestone reef formations, and slightly metamorphosed lavas (greenstones) that form the Wallowas and the Seven Devils Mountains. The Martin Bridge limestone crops out in the cliffs along the Lostine River, on Marble Mountain, and the Matterhorn. The dark sedimentary rocks and volcanic greenstones compose many of the intermediate ridges and peaks in the high Wallowas. Today some of the perimeter sediments are folded from their traumatic collision with the edge of the continent. Fossil shells attest to their oceanic origins.

The ancient ocean sediments and volcanic debris have been peeled away from the center of the Wallowas through erosion; they surround the perimeter of a large granitic intrusion that forms the central core of the Wallowas. Earlier writers, e.g., Baldwin (1976), suggested that this granitic batholith was related to the Idaho batholith to the east that is 75 to 100 million years old. However, Goldstrand (1994) places the age of the Wallowa batholith as 143 to 160 million years, older than the Idaho batholith.

Finally, to complete the geologic setting of the Wallowas and Seven Devils area, the granitic core and the remains of the island arc terrane surrounding it, rise above a sea of Columbia River basalt which flooded the area 12 to 15 million years ago. Although much of the Columbia River basalt has eroded away, it still caps prominent peaks in the Wallowas, e.g., Chief Joseph, Aneroid, and Twin Peaks.

Following the long episode of accumulation of many strata of flood basalts, the Wallowas were uplifted by faulting on two sides. The fault system responsible for the uplift is still active today. The entire Wallowa region is a horst or upthrust block (Bishop 1994). The fault on the north side of the range is most evident. There the escarpment is steep, particularly above 2285 meters (7500 ft) (Smith and others 1941). Except for some overlapping sediments and slumping on the north side, the line between the Blue Mountains ecoregion and the Columbia Plateau, here represented by the greater Wallowa Valley, is sharply delineated. The cold air drainage from the mountains and rainshadow effect gives the local Wallowa Valley climate continental extremes in temperature and precipitation.

The faulting that raised the domed structure of the Wallowas as much as 1525 meters (5000 ft) created a radial drainage pattern. Eagle Cap rises 2950 meters (9675 ft) as the hub and source of the major streams; at center stage, it steals the scene from the Mt. Sacajawea which at 3000 meters (9838 ft) is actually the highest peak in the Wallowas. In this varied geology, stream courses tend to follow faults and contacts between less resistant and more resistant rock. After uplift, the steep gradients increased the erosive power of the streams, cutting deep canyons. The upper sections of these deep V-shaped valleys were altered by the onset of the Pleistocene. Several times over the Pleistocene epoch 11,000 to 500,000 years ago, glaciers sculpted the major river valleys into deep U-shaped valleys; they carved the peaks into amphitheaters and aretes and rearranged erosional debris and sediments (Johnson and Simon 1987). Airline passengers on flights heading east out of Portland, Oregon, are routinely thrilled to the sight of the perfect terminal moraine enclosing Wallowa Lake on the north side of the Wallowa range.

The climate of the Wallowa Mountains is temperate and continental, but the continentality varies from northwest to southeast across the range. The southern slopes are quite dry and endure continental extremes in weather. The northwest part of the range, on the other hand, has a marine influence. Winter severity also varies according to the degree of continentality as well as elevation. Precipitation increases steadily with elevation; at elevations below 1220 meters (4000 ft), half of the total precipitation occurs during the winter months. Above 1525 meters (5000 ft), two-thirds of total precipitation falls as snow (Johnson and Simon 1987).

As in the other ecoregions with high relief, the dome of the Wallowas range is separated into several elevational zones. In the north, a mesic shrub community of ninebark, common snowberry, Rocky Mountain maple, and serviceberry grows beneath the xeric forest canopy. To the south, where the slopes of the Wallowas meet the Continental Zone Foothills subregion, a xeric shrub community of bitterbrush and mountain big sage grows beneath ponderosa pine and Douglas-fir at elevations of 1100 to 1220 meters (3600 to 4000 ft). The soils in the xeric forest zone are xeric and frigid. The Vitrandic and Ultic Argixerolls, Ultic Palexerolls, and Lithic Ultic Haploxerolls have a surface layer rich in organic matter with or without a clay enriched subsoil. Those with a thick mantle of volcanic ash are classed as Typic Vitrixerands.

Mesic Forest Areas (fig. 3, 11l)—The western Wallowas are still influenced by the marine weather systems coming through the Columbia Gorge. There are large areas of Mesic Forest (11l) in the western Wallowas above about 4000 feet. Mean annual precipitation ranges from 72 to 125 centimeters (30 to 50 in), most of it falling as snow. Snow persists late into the spring, shortening the frost-free period to just 60 days. Soils in the Wallowas Mesic Forest subregion are both cool (frigid) and cold (cryic), and usually moist (udic); they have a significant ash content and are the most productive soils in the Wallowas. They are classed as Typic Vitricryands, Typic and Alfic Udivitrands, Andic Eutroboralfs, Vitrandic Haploxeralfs, and Vitrandic Haploxerolls. The Mesic Forest zone here and surrounding the subalpine core of the Wallowas is characterized by grand fir and various understory shrubs and forbs, depending upon slope, aspect, and moisture availability. Subalpine fir becomes more common in the higher elevations. A grand fir/queen's cup beadlilly association is the most productive, growing in fine ashy soil. Grand fir with big huckleberry also has a wide range and a wider tolerance for rockier soil. In general, the character of the mesic forest community is similar to that in the Maritime-Influenced Zone to the west and north.

Subalpine Areas (fig. 3, 11m)—The Subalpine Area of the Wallowa Mountains begins at the transition to colder soils, deeper snowpack and a shorter growing season. Subalpine fir grows as low as 1370 meters (4500 ft) along perennial streams and in drainage headlands. Engelmann spruce is seral or codominant to subalpine fir in areas with adequate moisture and infrequent fire. Mountain hemlock makes a rare appearance in the northwest quarter of the Wallowas on sites with northeast or northwest aspects at elevations of 1830 to 2195 meters (6000 to 7200 ft). Mountain hemlock is a species that is suited to withstand the deeper snow in that maritime-influenced portion of the Wallowas.

Above 2286 meters (7500 ft), the subalpine parkland grades into alpine meadows. Historically, green fescue and sedges covered the high alpine meadows from 1798 to 2408 meters (5900 to 7900 ft). Following intense grazing pressure by sheep early in the century, many high-elevation plant associations have reverted to seral or exotic species. For more details, Johnson and Simon (1987) provide a thorough examination of plant associations and habitats in the Wallowa Mountains and the Snake River Canyon.

To the east the Wallowas blend with the fragmented remains of the Columbia Plateau bordering the deep Snake and Salmon river canyons. The ecoregion boundary there is a combination of the end of the metamorphic geology and the bottom of the eastern Mesic Forest zone of the Wallowas. East of there the Columbia River basalt dominates and changes the character of the ecosystems because of the elevation, aspect, and erosional patterns. These areas are separated out as the Canyons and Dissected Highlands (11f) subregion.

Canyons and Dissected Highlands (fig. 2, 11f; fig. 3, 11f)—The Canyons and Dissected Highlands (fig. 3, 11f) subregion is comprised of several disjunct areas: the eastern and southern edge of the block of mountains in southeastern Washington, the eastern Wallowas, and the isolated islands of former plateaulands cut by the Snake River canyons to the east of the main Blue Mountain anticline. The subregion is an extension at higher elevations of the Canyons and Dissected Uplands subregion of the neighboring Columbia Plateau ecoregion. At elevations of 1525 to 2135 meters (5000 to 7000 ft), the Canyons and Dissected Highlands subregion is high enough to be considered mountainous. However, it has the same topographic expression as the Canyons and Dissected Uplands; that is, the uplifted Columbia basalt plateau has been eroded to a series of knife-edge ridges cut by deep canyons. The region is in the lee of the Maritime-Influenced Zone (11c) to the west which creates a rainshadow effect. However, the climate is still fairly moist; the mean annual precipitation ranges from 38 to 100 centimeters (15 to 40 in).

The soils are a mixture of colluvial canyon soil and soil with a loess or ash mantle. Because of the presence of loess and ash, the xeric forest zone is relatively narrow and soon grades into a mixed ponderosa pine, Douglas-fir, western larch, and grand fir forest. The plateau soils are frigid and usually moist (udic). They are classed as Typic Udivitrands if they have a mantle of volcanic ash without a clay subsoil and as Alfic Udivitrands, Andic, or Vitrandic Eutroboralfs if they have a clay-enriched subsoil. Often on southern aspects in this region the dominant vegetation changes from bunchgrasses directly to Douglas-fir without an intervening ponderosa-pine phase. This is partly due to the loess content of the soil. Douglas-fir has an affinity for loess and its additional moisture-retaining capacity. Also, Douglas-fir is adapted to growing in the difficult environment of shifting colluvial soils on steep canyon slopes.

All areas of the Canyons and Dissected Highlands subregion border the Canyons and Dissected Uplands subregion of the Columbia Plateau except for the east side of Summit Ridge east of the Wallowas Mountains, where the terrain dives into the canyon depths of the Snake and Salmon River Canyons (11g).

Snake and Salmon River Canyons (fig. 2, 11g; fig. 3, 11g)—The Columbia River flood basalts buried the accreted terranes 13 to 16 million years ago, leaving only the highest Wallowas and Seven Devils Mountains protruding. The basalt dams blocked the flow of the ancestral Snake River, creating Lake Idaho. About 2 million years ago, headward erosion and stream capture created the present Snake River channel between Boise and Lewiston, Idaho. The drainage of Lake Idaho carved Hell's canyon to expose the foundation rocks of the Blue Mountains, the stranded islands of the island arc terrane. During the Pleistocene, the emptying of Lake Bonneville widened and deepened the Snake River canyon (Johnson and Simon 1987). The topographic relief at Hell's Canyon is 1525 meters (5000 ft) from the river to the tops of the Seven Devils Mountains, making it the deepest canyon in the United States.

The Snake and Salmon River Canyons (11g) subregion is a continuation of a similar subregion, the Canyons and Dissected Uplands, in the Columbia Plateau ecoregion to the north (see section 1 above). It was an option to retain these two canyons as part of the Canyons and Dissected Uplands subregion of the Columbia Plateau. The two subregions have a similar erosional pattern, a parallel series of knife-edged ridges cut into the basalt. They also have similar climate, precipitation pattern, and grassland vegetation. The climate in the canyon is hot and dry, with mild winters. Precipitation varies annually from 25 to 50 centimeters (10 to 20 in).

The Snake and Salmon River Canyons have been included in the Blue Mountains ecoregion in part because of their geographic location, surrounded as they are by the Wallowas and Seven Devils Mountains. In addition, these canyons differ from those to the north in the Columbia Plateau ecoregion by the presence, under a thick covering of Columbia River basalt, of metasedimentary and metavolcanic rock belonging to the Wallowa/Seven Devils island arc terrane that became part of the continent 100 million years ago.

These metamorphic rocks may produce deep soils on river benches; however, the soil is stony, and it retains little moisture. Bluebunch wheatgrass, Sandberg's bluegrass, and spiny greenbush are adapted to grow under these hot, dry conditions (Johnson and Simon 1987). Canyon slopes with a favorable northern aspect may have a covering of loess. Loess retains moisture better than colluvial soil; it fosters Idaho fescue associations and more mesic shrubs such as rose and snowberry (Johnson and Simon 1987).

The soils over the Miocene basalt flows are divided by elevation into those below 1067 meters (3500 ft) with a mesic temperature regime and those above 1067 meters (3500 ft) with a frigid temperature regime. Below 1067 meters (3500 ft), the aridic and xeric soils are dominated by Lithic, Aridic, and Typic Haploxerolls. Above 1067 meters

(3500 ft), the xeric soils in the cooler temperature zone are Lithic and Pachic Argixerolls and Lithic Haploxerolls. Vegetationally, bluebunch wheatgrass and Sandberg bluegrass are adapted to the driest areas; Idaho fescue dominates in the increased moisture of the middle to higher elevations, becoming mixed with snowberry and scattered ponderosa pine at the upper end of the canyons.

Continental Zone Highlands (fig. 3, 11h)—The Continental Zone Highlands (fig. 3, 11h) comprise the south central and southeastern Blue Mountains, those areas most in the continental climate regime. Low precipitation, high evapotranspiration, abundant sunshine, and high temperature extremes of 37.7°C to -23.3°C (100°F to -10°F), characterize the climate pattern in this section of the Blue Mountains. The stream density is less than elsewhere in the Blue Mountains, and intermittent streams are more numerous. The few major streams flowing south end in the interior drainage of the Harney Basin. The topography is not as steep as elsewhere in the Blue Mountains; it is an undulating landscape with broad open flats and stringers of woodland distributed up the draws. Isolated mountain peaks and buttes dot the landscape. Elevations range from 1067 meters (3500 ft) to near 2135 meters (7000 ft) (Paulson 1977).

The geology of the area is also different from regions to the north. Recent volcanics of Pliocene age, rhyolites and ash flow tuffs, cover these southern mountains as well as areas far to the south to northern Nevada (Walker 1990b, Walker and MacLeod 1991). Rhyolite is a moderately hard rock that is resistant to weathering. As a result, the soil formed from residuum and colluvium of rhyolite is often shallow and cobbly or gravelly. Most of the soils in this subregion are in the xeric soil moisture regime and in the frigid soil temperature regime. In the lower elevations, where ponderosa pine is the climax species, the major soil subgroups are Vitrandic and Lithic Haploxerolls as well as Lithic and Typic Argixerolls.

The vegetation cover of the Continental Zone has similarities to the central Blue Mountains and the southern Ochocos in the ponderosa pine/xeric shrub/bunchgrass associations. Ponderosa pine forest occupies the warmest, driest zones; it is the climax species in the lower elevations. The pine grows on a wide range of soils in a zone from 762 to 1675 meters (2500 to 5500 ft) where the mean annual precipitation is 41 to 89 centimeters (16 to 35 in). At about 1370 meters (4500 ft), the scattered pine/grassland savannah becomes a more closed canopy woodland with pine and juniper mixed with xeric shrubs. The most common xeric shrubs are big sage, mountain mahogany, bitterbrush, and squaw currant. These pine-shrub associations are found at elevations of 1220 to 1675 meters (4000 to 5500 ft). Of the understory plants, big sage indicates a very dry site, mountain mahogany indicates a stony, low productivity site, and bitterbrush a site higher in productivity (Hall 1973, Johnson and Clausnitzer 1992).

The especially early drought on xeric, ashy soil also produces several distinctive associations that are shrubfree. They are the ponderosa pine or Douglas-fir with pinegrass and elk sedge associations. Both plants are promoted by fire, but pinegrass prefers ash soil. These associations are found on southern exposures on droughty, thin soil from 1220 to 1980 meters (4000 to 6500 ft).

There is no appreciable Mesic Forest subregion in the upper elevations of the Continental Zone Highlands as there is in the other subregions of the Blue Mountains. In the higher elevations, grand fir is technically the climax with pinegrass and elk sedge understories. However, normally, the grand fir rarely matures because of the fire frequency (Hall 1973, Johnson and Clausnitzer 1992). Douglas-fir and grand fir associations do form a mixed forest at the moist end of the xeric soil moisture gradient. Douglas-fir climax associations may be found from 1220 to 1705 meters (4000 to 5600 ft) on all parent materials.

Continental Zone Foothills (fig. 3, 11i)—The Continental Zone Foothills (fig. 3, 11i) subregion bounds the southern perimeter of the Blue Mountains from a point near the southeast corner of Crook County on the southern flanks of the Ochoco Mountains, around the east side of the Elkhorn Mountains and Baker Valley, to the edge of the massive batholith in western Idaho. Elevations range from 1067 to 1615 meters (3500 to 5300 ft) in the eastern portion and from 1370 to 1585 meters (4500 to 5200 ft) in the west. Precipitation ranges from 25 to 40 centimeters (10 to 16 in), increasing with increasing elevation. The precipitation falls as light snow, spring or fall rains, or occasional summer thunderstorms. Land use is predominantly grazing, except in the irrigated valleys.

Geologically, the Continental Zone Foothills have three major subdivisions. The foothills from the Ochoco Mountains to the Willow Creek valley (near the Baker County/Malheur County line) form the first unit. They are underlain by lava flows and breccia of Miocene basalt and andesite. These volcanics cover a large area of the high desert in Oregon south to the Nevada border.

The second geologic subdivision, the hills and terraces bordering the Baker Valley area, south of the Wallowa Mountains to the Snake River canyon, is a continuation of the melange geology of the central Blue Mountains. The geologic landscape is a chaotic collection of volcanic island arc fragments, deep sea crust and sediments, and granitic intrusions, overlain in the south and east by Miocene basalts and andesites of the Powder River volcanics.

Finally, an arm of the Blue Mountains east of the Snake River extends south above the Snake River Plain to just north of Boise, Idaho. Geologically, this area is the southernmost extension of the Miocene flood basalts that inundated the Columbia Plateau. The basalt filled the topographic trough that follows the "suture zone" of the new (200 myr old) accreted terrain and the ancient continental land mass. The flood basalt also blocked the flow of the Miocene Snake River to create Lake Idaho. The southern foothills, running south of Huntington, Oregon, and east into Idaho, end at the margin of the valley sediments deposited in Lake Idaho, what is now the Snake River Plain.

However, from an ecological point of view, geologic makeup is subordinate to the other landscape characteristics that make this subregion distinctive. The ecosystem is a reflection of the consistency of the climate, soil, and vegetation cover. The entire area is solidly within the continental climate zone. The combined land masses of the Cascade Mountain Range and the Blue Mountains to the northwest effectively block any marine influence. As a result, the Continental Zone Foothills subregion experiences wide temperature ranges, xeric and aridic soil regimes, high evapotranspiration, and high early season moisture stress for vegetation. The few perennial streams draining the Ochocos and Malheur Mountains empty into the marshes of the Harney Basin to the south. To the east, the subregion is surrounded by higher mountain ranges, the Elkhorns and Wallowas, and thus has more perennial streams; but up away from the streams, the upland areas have even drier soil regimes than the foothills farther west.

The soils of the western portion of the foothills region have basalts, andesites, and rhyolites as parent material. They are shallow to moderately deep soils with xeric moisture and frigid temperature regimes. The dominant soil families are Typic, Lithic, and Pachic Argixerolls as well as Lithic Haploxerolls. The surface layer of these soils is typically very stony loam with a gravelly clay loam subsoil.

The soils of the eastern foothills with mixed geology are deeper in general than those to the west, except on the steeper hill slopes. The soils on terraces below an elevation of about 1220 meters (4000 ft) have an aridic moisture and a mesic temperature regime. The soils above 1220 meters (4000 ft) have a xeric moisture and a frigid temperature regime. The surface layer is typically a silt loam or loam with a clay loam or clay subsoil. The soil families on the lower terraces are Aridic and Aridic Calcic Argixerolls, Xeric Argidurids, and Xeric Haplocambids. On the higher terraces, the soils often have a hardpan or dense clay layer within 1 meter (40 in) of the soil surface. Here the major orders are Typic and Pachic Palexerolls and Typic Durixerolls. The rolling hills between the Baker valley and the Snake River canyon and further east into Idaho have shallower, more cobbly soils. They are classed as Calcic, Lithic, Typic, and Pachic Argixerolls.

The vegetation of the Continental Zone foothills is characterized by a diverse desert shrub community that varies according to the soil depth, texture, and productivity. The poorest sites, with shallow soil, winter waterlogging, and desert pavement, grow stiff sagebrush or low sage with some juniper on the scabland "biscuits." Mountain mahogany grows on rocky sites in a wide elevation range. Somewhat deeper soils over varied substrate will support bitterbrush, mountain snowberry, and mountain big sage with bunchgrasses in associations. Both mountain mahogany and bitterbrush are valuable wildlife resources, providing cover and winter range for mule deer. Rodents, passerines, and upland game birds utilize the fruits and buds of bitterbrush (Johnson and Clausnitzer 1992). Bitterbrush decreases to the east where it becomes scarce on the southern flanks of the Wallowas (Johnson and Simon 1987).

Batholith Contact Zone (fig. 3, 11j)—In westernmost Idaho, an arm of the Blue

Mountains forms the transition from the dry Snake River Plains to the Northern Rocky Mountains. This area is included with the Blue Mountains because its climate, geology, soil, and vegetation are consistent with those elsewhere in the Blue Mountains. There is still a slight marine influence from the northwest in this area; the climate becomes more extreme to the east. The moderated climate, along with soils developed from the basaltic parent material, produces a typically Blue Mountain vegetation. Elevations range from about 1370 to 2530 meters (4500 to 8300 ft), high enough for a Mesic Forest Zone and a Subalpine Zone. This is the southeastern limit of the Columbia River basalts. The region is transitional because it bridges the Columbia River basalts and the massive Idaho granitic batholith; the rock has been highly metamorphosed to schists, amphibolite, and greenstones (McKee 1972).

Ponderosa pine dominates the forest community between 914 and 1980 meters (3000 and 6500 ft). Its upper limits are determined in part by the depth of snowpack. In this transitional area, Douglas-fir assumes a similar role to the one it takes farther north in the Canyons and Dissected Highlands subregion. It is found on north-facing slopes from 945 to 2164 meters (3100 to 7100 ft) on a variety of substrate with an understory of ninebark. It is adapted to the more mesic conditions there as well as the colluvial soils of the canyons (Steele and Geier-Hayes 1989). A Douglas-fir/pinegrass association is also prevalent in this zone of slight maritime influence (Steele and Geier-Hayes 1987).

Mesic Forest Section (fig. 3, 11l)—Above 1525 meters (5000 ft) in the Mesic Forest

Zone, grand fir and blue huckleberry grow on both granitic and volcanic substrate, between 1525 and 1890 meters (5000 and 6200 ft). Again, due to the slight residual marine influence, this area is the southeastern outpost for grand fir (Steele and Geier-Hayes 1987). The major portion of the mesic forest zone occurs on the northwestern to northeastern aspects. The common seral species in the mesic forest zone are ponderosa pine, western larch, lodgepole pine, and Engelmann spruce.

Blue Mountain Basins (fig. 2, 11k; fig. 3, 11k)—This ecoregion is a composite subregion composed of scattered basins large enough to be depicted at the 1:250,000 scale. Structurally, the basins may be the result of depressions or synclinal downwarps in the flow sequences of the flood basalts (e.g., Ukiah Basin, John Day Basin), erosion of a soft substrate in ash or tuff areas (Fox Basin), or depressions defined by faults (Grande Ronde Valley and Baker valleys). Pyroclastic rocks and tuffaceous sedimentary rocks were deposited in many basins, for example, the John Day, Fox, Bear, and Logan valleys. The John Day basin was filled with gravelly, sedimentary rocks from the rising Aldrich and Strawberry Mountains. Airborne ash-fall tuff characterizes the basins of the southern perimeter of the Blue Mountains, Baker Valley, the Durkee and Unity Basins, Paulina, Burnt River, and the lower Powder River valley (Walker 1990b).

The Grande Ronde valley, near La Grande in northeastern Oregon, is a fault-bounded valley graben. Hot springs, such as those at Hot Lake, are present around the periphery of the valley, indicating that geologic unrest is continuing. The basin is very deep to bedrock, filled with up to 610 meters (2000 ft) of sediments to its present day elevation of 785 to 850 meters (2600 to 2800 ft). The valley fill is a variety of Pleistocene deposits of gravels and silts, lacustrine deposits, alluvial fans, and loess from the Columbia Plateau to the north. The lake bed silts are still poorly drained; they are classified as Haploxerolls, Endoaquolls, and Haplaquolls. Settlers drained most of the marshland for pasture and hay, but there is a remnant left in the southwestern valley at Ladd Marsh. The valley also has a significant deposit of loess running from the central valley to its northern edge. The soils here are very deep to bedrock; they are classed as Haploxerolls, Argialbolls, and Argixerolls. The potential natural vegetation on the terraces and loess hills consists of Idaho fescue, common snowberry, and Sandberg's bluegrass. On the floodplains, tufted hairgrass, redtop, and sedges are associated with wetter soils. Today, the majority of the valley is farmed. The Grande Ronde River and its tributary streams, many of which have been channelized, provide irrigation water to grow hay, commercial grass seed, alfalfa, and peas.

The Grande Ronde valley is transitional to the dryer, loess covered, Columbia Plateau to the north; however, structurally the valley is wedded to the Wallowa Mountains. Also, the climate of the valley is still moderated by the marine influence from the west. Precipitation amounts vary from 32.5 centimeters (13 in) in the dry southern valley to 60 centimeters (24 in) at the eastern end of the valley. For these reasons, the valley was included in the Blue Mountains ecoregion rather than in the Columbia Plateau.

The Baker valley of the eastern Blue Mountains is also a fault-bounded depression in the melange geology of the Baker terrane (see the geologic explanation under the Melange subregion). Elevations range from 610 to 1675 meters (2000 to 5500 ft). The valley and surrounding grasslands encompass the alluvial floodplains and terraces of the Burnt and Powder rivers. The basin is firmly located in an arid area of continental climate. The mean annual precipitation ranges from 23 centimeters (9 in) in the lower elevations to 40 centimeters (16 in) on the higher terraces. Soils below 1220 meters (4000 ft) have an aridic soil moisture regime, meaning they receive less than 25 centimeters (10 in) of precipitation annually. The aridic soils also have a warmer temperature regime (mesic). The east edge of the basin has abundant alkaline soils due to poor drainage and high evaporation rates. The shrub greasewood is abundant there. The floodplain soil is deep silt loam or silty clay loam, classified as Pachic Haploxerolls or Typic Haplaquepts. Soils on the terraces include Aridic Argixerolls, Xeric Argidurids, and Xeric Haplocambids.

Finally, many of the scattered depressions filled with airborne ash and pyroclastic volcanic debris constitute the high elevation meadows. The high meadows are often also alluvial, with a high water table and with soils containing clay or silt. Streams are slow and meandering, and if not channelized, they have a dynamic interaction with their floodplains. These unconstrained sections of stream provide pool habitats so important to salmonids for refuge and rearing (McIntosh and others 1994). The altitude and year-round moisture make these basins unsuitable for cultivation, but they are grazed heavily by cattle and elk. The vegetation includes sedges and tufted hairgrass. Meadows in poor condition are dominated by Kentucky bluegrass. The riparian areas, if still present, support willow. Trampling and overgrazing on the fine silty substrate may cause the incision of the stream bed, lowering the water table and stranding the wet meadow without a source of ground water.

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SECTION 3—LANDSCAPE-LEVEL ECOREGIONS FOR SEVEN CONTIGUOUS WATERSHEDS, NORTHEAST OREGON AND SOUTHEAST WASHINGTON

by Sharon E. Clarke, Mark W. Garner, Bruce A. McIntosh, and James R. Sedell

Introduction

Change is constant; streams have undergone millions of years of geological and climatic processes; however, the rate of change of the present landscape is alarming. Fifty years ago, spring chinook (*Oncorhynchus tshawytscha*) spawned in streams where they may never spawn again. Decreased ranges and declining numbers of other anadromous stocks and resident species are also evident. The extent, complexity, and critical nature of this problem has been well documented (Frissell 1993, Henjum and others 1994, Nehlsen and others 1991, Williams and others 1989). Habitat destruction including loss of large pools, increased sedimentation, loss of complexity, decreased flows, and increased water temperature, is listed as a major factor in this rapid decline (Frissell 1993, Henjum and others 1994, Nehlsen and others 1991, Williams and others 1989). These stream habitat characteristics are influenced by instream and riparian zone processes as well as upland processes (FEMAT 1993, Frissell and others 1986, Gregory and others 1991, Henjum and others 1994, Lotspeich and Platts 1982, Platts 1980) operating at many spatial and temporal scales.

To recognize the role of upland processes in modifying stream habitat, we developed landscape-level ecoregions (Level V). In the text, we use the term *ecoregions* as a general term referring to ecological regions defined at any spatial scale; *landscape-level ecoregions* refer to regions specifically delineated in this study, that is, an area defined by specific landscape-level criteria to be smaller in scale than national scale ecoregions (Level II and III) or a subregion (Level IV). Specific landscape-level criteria might be uniform soil, climate, topography, geology, geomorphology, or vegetation.

The spatial component of stream ecosystems was recognized by using a hierarchical landscape stratification. The landscape stratification followed Warren's (1979) ideas of a classification system for watershed management adapted by Omernik (1987, 1995). Gallant and others (1989) described the process and uses of landscape stratification at the national and subregional scale. We used the concepts of hierarchical stratification for aquatic organisms developed by Frissell and others (1986), Lotspeich and Platts (1982), Minshall (1988), Platts (1980), and Warren (1979).

Omernik and Griffith (1991) argue against the sole use of a hydrologic framework for the study and organization of ecosystems. They state that, "although the longitudinal linkages emphasized in the river continuum concept are important, we must also look for important lateral linkages with regional characteristics." Ecoregions account for changes in stream habitat characteristics derived from changes in the surrounding land and watersheds account for the interconnectedness of water (Whittier and others 1988). Combining landscape stratification with watershed delineations is appropriate for this study because the pathways for anadromous fish distribution are determined by watershed linkages and landscape characteristics. To foster this union, our study area was defined by watershed boundaries. For analysis, finer-scale watershed delineations can be easily overlaid, with a Geographic Information System (GIS), on ecoregions using a "cookie cutter" approach. Landscape-level ecoregions form a bridge between finer-scale stream classifications and coarser-scale ecoregions (Bryce and Clarke 1996). The choice of which scale in the hierarchy to use depends upon the question or management problem being addressed (Minshall 1988).

One of the cornerstones of Warren's (1979) classification scheme is the idea of using the potential capacity of the system. He suggests that "it is capacity of a system not any particular performance, that most interests us. It is so because performances, such as structure, of systems are in continuous flux and we want to know what we can expect of a system." He goes on to say " we cannot have a system whose essential kind has changed placed in a different class every time its performance changes, as it will with environmental change. It is useful to distinguish between the potential capacity of a system and the different realized capacities it could come to have under different developmental environments and at different stages in a given environmental system through time." He defines potential capacity "as all possible performances in all possible developmental environments."

The ecoregion approach assumes that: (1) streams are a reflection of the watersheds that they drain and (2) ecoregions reflect the variability in the potential capacity of streams. Climate, geomorphology, geology, topography, potential natural vegetation, and soil influence substrate, water quantity and quality, habitat complexity, and riparian vegetation. The relative influence, or importance, of each varies from one region to another. The grouping of areas having similar landscape characteristics allows a better comparison of the potential capacities of streams of similar size between each region.

Ecoregions have been developed at the national (Omernik 1987, 1995) and regional/state level (Clarke and others 1991, Gallant and others 1989, Griffith and Omernik 1991, Griffith and others 1994, Griffith and others 1995, Thiele and others 1992) for research, resource management, and regulatory use. Landscape-level ecoregions are intended to help address issues of research and management at a local scale by (1) anticipating the effects of different types and intensities of land uses, (2) providing a target for restoring stream habitats, (3) selecting the monitoring and research sites, and (4) extrapolating data from research and monitoring sites to other streams with similar potential capacity.

Many studies are conducted outside of the context of their ecosystems. By using ecoregions to view the entire fabric of an ecosystem, not just a single thread, processes operating in one area and not in others may be demonstrated, and some complex effects and relationships may come to light. For example, meadow and desert streams obtain much of their energy from within the stream as opposed to forested areas where the primary energy source is input from litterfall (Murphy and Meehan 1991). The scientific literature contains many studies attempting to understand how fish respond to single habitat variables, but attempts to study the interactions of many habitat variables are few (Petersen and others 1992).

We know that landscape characteristics influence stream habitat. However the effects of multiple interactions, sometimes acting synergistically and sometimes antagonistically, are difficult to predict. Instead of trying to knit together all of the possible contributing factors and predict an outcome or prove a hypothesis (experimental, bottom-up approach), we have taken a classification (observational, top-down) approach. However, the knowledge gained by other researchers using an experimental approach is essential to evaluate the potential influence of any one landscape characteristic on stream habitat. In this iterative process, the results of the observational approach help to refine further process-level research. The two approaches are symbiotic, not competitive.

Objectives of the Project

The goal of this project was to provide a tool to help scientists and managers better understand the relationship between landscape characteristics and stream habitat for seven contiguous watersheds within the Blue Mountain and Columbia Plateau ecoregions of northeast Oregon and southeast Washington. The two objectives of this research were to use the ecological framework developed for ecoregions and subregions to define landscape-level ecoregions for seven contiguous watersheds in the Blue Mountains and Columbia Plateau ecoregions and to describe the rationale used to delineate the regions.

These landscape-level ecoregions were developed in concert with the refinement and subdivision of the Columbia Plateau and Blue Mountains ecoregions to ensure the subregion and landscape-level boundaries coincided (above section 1, above section 2). The quality of these ecoregions were partly dependent upon the quality, resolution, and scale of the thematic maps used to derive them. Using multiple landscape characteristics and several sources alleviated some of the problems associated with an individual map by allowing for comparisons between the layers and between the sources within the layers. For example, soil maps usually provided information on vegetation which was compared to vegetation maps. A detailed description of the merits and drawbacks of each of the map sources was intended to help potential users of the maps evaluate the usefulness of the classification and point out where improvements can be made as additional source material becomes available.

The value of a particular classification scheme is largely a function of the goals and objectives of a project. In this report, we attempt to explain as explicitly as possible the reasoning employed in delineating landscape-level ecoregions. This explanation should help potential users of the map judge the usefulness of this classification for their purposes.

Connection to Other Approaches

Many approaches to understanding or managing complex interactions between the uplands and stream habitat have been studied such as:

- Range of natural variability[3] (Wissmar 1993).
- Aquatic conservation strategy (FEMAT 1993).
- Biologically based habitat standards (Rhodes and others 1994).
- River continuum (Minshall 1988, Minshall and others 1985, Vannote and others 1980).
- Stream-habitat classification (Bisson and others 1982, Cupp 1988, Frissell and others 1986, Hawkins and others 1993, Lotspeich and Platts 1982, Montgomery and Buffington 1993, Nawa and others 1991, Rosgen 1985).

Landscape-level ecoregions are not so much an approach as they are one tool that can be used in conjunction with these approaches and other tools to assess ecosystem condition and change through time and the effects of disturbance.

Range of natural variability—The approach using range of natural variability applies standards that define the limits of acceptable and unacceptable ecosystem conditions for streams within the spatial and temporal variabilities inherent in dynamic ecosystems based upon a long-term stream monitoring program (Wissmar 1993). One objective of the monitoring program is to assess the effectiveness of ecosystem restoration programs, including defining criteria for success. One of the important components in the development of a restoration plan and in defining criteria for success is determination of the present status and historical review of disturbances induced by natural events and human activities. Wissmar (1993) states that "this information can be obtained by defining the landscape in terms of bedrock geology, geomorphic landforms, hydrologic regimes, and distribution of stream and riparian habitats." Depending upon the objectives, subregions or landscape-level ecoregions may provide a suitable stratification of the landscape. It may also be useful to embed a finer-scale stream classification within the coarser landscape-level ecoregions to obtain another layer of stratification.

Aquatic conservation strategy—FEMAT (1993) propose a system of interim riparian reserves, key watersheds, watershed analysis, and watershed restoration as their Aquatic Conservation Strategy. They state "that within a physiographic province, similar geographic and topographic features control drainage network and hillslope stability patterns. Riparian reserve design may vary as a result of these differences." Subregions or landscape-level ecoregions may provide additional information in assessing drainage network and hillslope stability patterns because of their inclusion of information on soil, geology, and vegetation.

Watershed analysis uses maps of topography, stream networks, soils, vegetation, and geology along with sequential aerial photographs, field inventories and surveys, census data on species presence and abundance, disturbance and land-use history, and other historical data to provide information on what processes are active within a watershed, how these processes are distributed in time and space, what the current upland and riparian conditions of the watershed are, and how all these factors influence riparian habitat and other beneficial uses. Landscape-level ecoregions combine most of the map types used in the watershed analysis and may provide a template on which to place the other types of information for a watershed. Specific monitoring objectives are derived during the watershed analysis process and are tailored to each watershed. Riparian areas selected for monitoring are dispersed among the various landscapes because of the influence of past disturbance, topography, climate, and other factors on the natural conditions of stream habitat. Here too, we feel subregions or landscape-level ecoregions may provide guidance in selecting monitoring sites.

Biologically based habitat standards—Rhodes and others (1994) set standards for stream ecosystems based on available information about the biological-habitat requirements of salmon. They state that "meeting the habitat requirements of salmon species must be the biological bottom line of efforts to protect and restore spawning and rearing habitat consistent with efforts to stabilize and restore the listed salmon runs." No further degradation is allowed in stream systems that currently exceed the biologically based habitat standards. Rhodes and others (1994) agree that classification is a useful tool for looking at questions of attainability of stream-habitat criteria and channel response to perturbation. Using subregions or landscape-level ecoregions may help fine-tune the habitat standards to reflect differences in the potential capacity of streams. For example, biologically based habitat standards should be the lowest acceptable standards, but for some systems attaining these standards still represents a degraded condition, and higher standards should be imposed. In other systems, natural conditions do not meet the biologically based habitat standards. Efforts to meet the habitat standards in these streams may be unrealistic, short-term, and expensive. These efforts could detract from other more productive efforts. Subregions or landscape-level ecoregions may be useful in identifying areas where biologically based habitat standards are too low or difficult to achieve due to the inherent potential capacity of the system.

River continuum—The river continuum concept (Vannote and others 1990) asserts that stream ecosystems are connected and that conditions change accordingly from headwaters to the mouth of a river. Because the differences created along a river continuum are based on the landscape in which it is embedded, the idea of continuity (the river continuum concept) needs to be merged with the idea of context (regional classification). The effects of upstream and upslope regions and increasing stream size need to be recognized in any interpretation of stream ecosystem research. Landscape classification provides a logical rationale for ordering and testing relationships.

Stream-habitat classification—Landscape-level ecoregions were developed to compliment stream-habitat classifications (Bryce and Clarke 1996). Stream-habitat classification is finer-scale and focuses on the stream channel and valley floor. The merits of stream-habitat classification are discussed by Bisson and others (1982), Cupp (1988), Frissell and others (1986), Hawkins and others (1993), Lotspeich and Platts (1982), Montgomery and Buffington (1993), Nawa and others (1991), and Rosgen (1985). Stream-habitat classification coupled with a landscape classification of the entire watershed recognizes the connectedness of the entire drainage network (Bryce and Clarke 1996, Frissell and others 1986, Lotspeich and Platts 1982). In addition, O'Neil and others (1986) suggest that using a hierarchical approach allows for patterns to emerge which may be masked at the next lower level in the hierarchy. Landscape-level ecoregions may identify patterns masked by the increased variability of finer-scale stream classifications. However, while stream-habitat classification generally delineates the current state of the system, landscape-level classification aims to define potential capacity. This difference makes interpretations and comparisons between these two methods difficult.

Rationale for Delineating Landscape-Level Ecoregions

Landscape-level ecoregions were developed to aid research and management of anadromous fish and their habitat.[4] To provide a rationale for using a landscape classification to understand fish distribution and abundance, we described the connections between landscape characteristics and stream-habitat characteristics and between stream-habitat characteristics and fish distribution. The primary stream-habitat characteristics that influence fish distribution and abundance were substrate, habitat complexity, riparian vegetation, water quality and quantity, and biota. Landscape characteristics can directly or indirectly influence these stream-habitat characteristics. By identifying areas that are fairly homogenous in their mix of landscape characteristics we hypothesized that the potential capacity and the reaction to both natural and anthropomorphic disturbances of streams will be influenced by the individual landscape characteristics that constitute landscape-level ecoregions.

Most of the literature discussing stream-habitat characteristics is focused on disturbed conditions. We have used this information and related it to analogous natural conditions. In doing so we recognized that a natural system has more resiliency than a disturbed system.

Substrate—Topography, climate, vegetation, soil, and geology influence sediment production and erosional processes (Swanson and others 1987). These landscape characteristics influence the particle size and amount of sediment by affecting the erosion, transport, and storage of soil particles. Table 3 shows the factors influencing sediment production along with the relative risk to stream-habitat productivity.

Surface erosion and mass movements contribute sediment to streams. Surface erosion involves detachment and movement of soil particles. Detachment is influenced by soil texture and the amount of protection by vegetation. Precipitation intensity and duration, soil infiltration rate, and slope gradient and length influence soil movement (Swanson and others 1987, Swanston 1991). Where and when mass movements occur, their size, and amount of material transported are controlled by slope, parent material, depth and degree of weathering, and soil saturation (Swanston 1991). The downstream movement and deposition of sediment are influenced by channel morphology, water quantity, and amount and size of material (Swanston 1991). Once the sediment enters the stream, it may move as either suspended sediment or bedload, depending upon particle size and flow. Small headwater streams are usually more prone to erosion because both the sideslope and channel gradient are steeper (Naiman and others 1992). Interaction with the uplands is also greater for these small streams because there is a less-developed riparian buffer strip to act as a storage area for sediments.

Erosion and sedimentation are natural processes that contribute to a healthy stream ecosystem by providing the sources and surfaces necessary for aquatic habitat (Naiman and others 1992). Both the particle size and amount of sediment in a stream influence stream habitat. High concentrations of fine sediment may lead to overloading of substrate material (Heede and Rinne 1990). Fine sediment may directly reduce the egg-to-fry survival and fry quality of anadromous salmonids by (1) decreasing water flow through the gravel of the redd therefore reducing dissolved oxygen and causing suffocation of eggs and alevin and (2) creating a physical barrier to emergence (Bjornn and Reiser 1991, Everest and others 1987, Murphy and Meehan 1991, Petersen and others 1992, Rhodes and others 1994, Swanston 1991). Rhodes and others (1994) report that decreased interstitial space from sedimentation results in the elimination of fry from habitat, alters the food base, and reduces available winter interstitial habitat and consequently may increase pre-smolt mortality.

Indirect effects of sedimentation on salmonids include changes in channel morphology, increased turbidity, and decreased food availability (Everest and others 1987, Murphy and Meehan 1991, Petersen and others 1992, Swanston 1991). An abundance of coarse-grained sediments may increase infiltration and percolation, thereby reducing surface flows during dry conditions (Everest and others 1987). Different salmonid species require different gravel substrate sizes for spawning; large fish can use larger substrate materials than can small fish (Bjornn and Reiser 1991). Gravel-sized material in riffles provides the primary food-producing areas for fish (Heede and Rinne 1990).

Habitat complexity—Bisson and others (1982) define habitat complexity as the distribution and abundance of habitat types. Lichatowich and others (1995) add that complexity includes connectivity throughout the salmonid's range. They define connectivity as the ability to migrate at the appropriate time between links in the habitat chain. Habitat complexity is controlled by discharge, sediment load, bank characteristics, and structural features such as large woody debris (LWD), bedrock, boulders, and sediment wedges (Murphy and Meehan 1991, Sullivan and others 1987, Swanston 1991). The presence of these structural features is determined by local geology and active hillslope-and-channel erosion processes (Sullivan and others 1987, Swanston 1991). LWD input varies considerably, depending on species of trees growing alongside a stream, soil stability, valley form, climate, and lateral channel mobility (Bisson and others 1987, Maser and Sedell 1994, Sedell and others 1988). Inputs may be either frequent chronic inputs or intermittent, sizeable inputs (Maser and Sedell 1994) depending on slope, climate, soil, and bedrock type. Pool-forming agents are influenced by gradient, vegetation, and geology. For example, in high gradient streams, pools form around structural features; and in low gradient systems, most pools are found in meander bends.

Habitat complexity enhances diversity of species and age-classes and translates into a more resilient ecosystem (Franklin 1992, Hawkins and others 1993, Sullivan and others 1987, Vannote and others 1980). Successional patterns of fish assemblages in streams are usually spatial rather than temporal. Specialization for temporal stages of ecological succession are not observed (e.g., pioneering species); periodic disturbances such as drought or floods cause species to relocate (Marcot and others 1994, Margalef 1960). A complex channel provides the needed refuges for such relocation (Sedell and others 1990). Floodplains and other seasonally wetted areas provide access for aquatic organisms to off-channel habitats during high flows (Sullivan and others 1987). Anchored driftwood and standing vegetation provide quiet water refuges during floods (Maser and Sedell 1994, Sedell and others 1988). Lichatowich and others (1995) identify the distribution and quality of salmon habitats in a watershed as one of the three elements important to the life history-habitat relationship of individual stocks. Life-history diversity dampens the risk of extinction or reduced production in fluctuating environments (Lichatowich and others 1995).

Habitat complexity can be organized hierarchically. Gregory and others (1991) and Frissell and others (1986) use the terms *reach*, *channel unit* (pool/riffle), and *subunit* (microhabitat) to describe the hierarchical levels. Habitat complexity is a function of diversity within and between levels. Gregory and others (1991) define reaches as sequences of channel units with distinct hydraulic and geomorphic structures reflecting different processes of formation. They describe a reach by the type and degree of local constraint imposed on the channel and valley floor. Constrained reaches tend to have relatively straight, single channels; unconstrained reaches in natural systems are characterized by complex commonly braided or meandering channels and extensive floodplains. Low gradient, wide valley bottoms, large woody debris, and poor drainage increase the occurrence of braided channels. In larger rivers where LWD does not span the channel, debris accumulations along the bank cause meander cutoffs and may create well-developed braided channels (Bisson and others 1987). A meandering stream provides diverse flows and increases the probability that the spawning and rearing needs of different life history stages of fish will be met (Heede and Rinne 1990).

At a finer scale, the mix of channel units (e.g., pools, riffles, and glides) contributes to habitat complexity. Channel units are differentiated on the basis of water-surface slope, width:depth ratio of the channel, and extent of turbulent, high-velocity flow (Gregory and others 1991). Channel-unit complexity provides favorable water-quality conditions, food supply, resting and hiding habitat within swimming distance (Heede and Rinne 1990). Pools provide a feeding area where little effort may be needed to hold position against the current (Bisson and others 1987, Maser and Sedell 1994). Migrating adults and juvenile salmon are dependent on pools for shelter from predators and refuge from low summer flows and high winter flows (Petersen and others 1992). Deep pools provide a variety of micro-habitats that allow different species of fish and/or fish of the same species but of different ages to coexist (Maser and Sedell 1994).

LWD plays an integral role in creating habitat complexity. Debris creates complex pool types such as dammed pools, plunge pools, lateral scour pools, and backwater or eddy pools (Bisson and others 1987, Bisson and others 1992). Local reductions in stream flow caused by LWD provide foraging sites for fish (Sedell and Beschta 1991). LWD decreases the erosive effects of flood water, including reinforcing meanders (Beschta 1991, Naiman and others 1992, Petersen and others 1992). In addition, LWD alters the stream profile and reduces local gradient (Franklin 1992, Swanston 1991).

Gregory and others (1991) define subunits as local hydraulic features created by boulders, logs, or gravel bars at scales less than the active channel width. They describe subunits as transitory features over annual hydrological cycles, changing rapidly with rising or falling water levels. Subunit complexity is provided by structures such as wood, boulders, and gravel bars. Diversity within subunits provides cover as protection from predators, competitors, or variation in streamflow. Cover is provided by LWD, overhanging vegetation, rubble, boulders, undercut banks, and water depth (Sullivan and others 1987). Low velocity areas downstream of boulders or other flow obstructions constitute resting, feeding, and spawning habitat (Heede and Rinne 1990). Stored gravel behind debris may provide excellent spawning habitat (Swanston 1991).

Water quantity—The amount, timing, intensity, and type of precipitation are influenced on a broad spatial scale by climatic processes, modified locally by topography and vegetation. Precipitation can be either stored as snow or immediately discharged into the stream as overland or subsurface flow. Infiltration rates, storage capacity, and transmission rates are related to soil characteristics (Swanston 1991). The major factors controlling stream flow are channel gradient, watershed size, type and density of vegetation cover, precipitation characteristics, topography, and soil infiltration rates.

The amount and timing of stream flows affect fish populations and all physical stream characteristics. Water quantity influences stream temperature, erosion processes, weathering rates, hillslope and channel sediment transport and deposition, channel morphology, current velocity, and riparian vegetation. The quantity and duration of stream flows are important to migrating salmon (Bjornn and Reiser 1991) and for the stability of spawning gravel (Petersen and others 1992).

Riparian vegetation—The occurrence and type of riparian vegetation are mainly controlled by channel geomorphology, the spatial position of the channel in the drainage network, soil, and climate (e.g., hydrologic regime) (Naiman and others 1992). Riparian vegetation contributes terrestrial invertebrates to streams as a food source for fish and organic matter as an energy base for stream biota (Beschta 1991, Gregory and others 1987). The indirect role of riparian vegetation in providing fish habitat is extensive. In summer, riparian vegetation provides shade to streams and lowers summer temperatures; and in winter, riparian vegetation moderates thermal temperature losses from streams and retards the formation of ice (Beschta 1991, Franklin 1992). Riparian vegetation reduces flow velocities, which allows for deposition of sediments and contributes to the long-term accretion of alluvium on floodplains (Beschta 1991). The root systems of riparian vegetation help to stabilize the banks during high flows (Beschta 1991, Franklin 1992, Sedell and Beschta 1991). Riparian vegetation is the main source for LWD, contributing to habitat complexity by affecting the dissipation of stream energy and creating local channel scour and deposition (Beschta 1991). Riparian vegetation slows the flow of water allowing it time to infiltrate into the bank. This infiltration helps to decrease peak flows, maintain local water tables and extend base flows through summer months (Wissmar and Swanson 1990).

Biota—The important biotic components of salmonid habitat are inter- and intra-species interaction and food sources. Species interactions are largely a function of the other physical components that have been discussed such as habitat complexity. Salmonids are opportunistic feeders that eat aquatic and terrestrial invertebrates. Food abundance along with physical habitat and salmonid behavior interact to determine the carrying capacity of a stream (Murphy and Meehan 1991). The relative importance of food is seasonally dependent. Food is more important in summer than cover, and in winter the opposite is true, although exceptions are numerous (Murphy and Meehan 1991).

Current velocity, temperature, substrate, vegetation, and dissolved substances influence the abundance and distribution of aquatic invertebrates. Of lesser importance are susceptibility to drought and floods, species competition, shade and zoogeography (Hynes 1972). These factors are influenced by landscape characteristics

Energy for food is available to a stream from two types of sources: autochthonous (photosynthesis within the stream) and allochthonous (decomposition of terrestrial organic matter) (Murphy and Meehan 1991). The three basic autochthonous forms are phytoplankton, periphyton, and vascular macrophytes. Each form characterizes streams of different sizes, gradient, and exposure to sunlight. The five main allochthonous inputs are: (1) streamside litterfall, (2) groundwater seepage, (3) soil erosion, (4) fluvial transport from upstream, and (5) animal activities (Murphy and Meehan 1991). Movement of organic matter depends on stream flow, particle size, and retentive capacity of the channel.

Water quality—In natural streams there is a wide variability in water quality due to the large number of controlling factors. Fish production can be altered by activities that affect water quality and water quantity or regimen (Meehan 1991). Naiman and others (1992) focused on five elements of water quality in the Pacific Northwest Coastal Ecoregion; nitrogen, phosphorus, turbidity, temperature, and intragravel dissolved oxygen (DO). Landscape factors are important in controlling water quality in Pacific Northwest Coastal Ecoregion streams (table 4).

Both nitrogen and phosphorus are important elements in the food chain (Naiman and others 1992). Turbidity, usually caused by suspended silt and clay particles, has wide-ranging effects on salmonids, invertebrates, and other aquatic organisms. Intragravel DO is reduced by turbidity and sedimentation and is critical for salmonid reproduction, invertebrates, and other aquatic life.

Seasonal and diel stream temperature influences: (1) trophic structure and composition, (2) habitat selection, and (3) fish metabolism, development, and activity (Beschta and others 1987). The influence of temperature on habitat selection was demonstrated in Oregon by Bond and others (1988) who found that when looking at summer stream temperature, significantly distinct habitat-use patterns appeared for 17 out of the 25 native species analyzed. Stream temperature is very important for bull trout; they require very cold water for most of their life history. Henjum and others (1994) found that published temperature tolerances for bull trout are much lower than for other salmonids 4 to 10°C (39 to 50°F) and egg incubation 1 to 6°C (34 to 43°F). Effects of higher stream temperature can be both positive and negative, although the positive effects have only been indicated at the reach level in fairly cold systems.[5] Warm temperatures: (1) increase the potential for competition with warm water species, (2) reduce rearing area availability, and (3) increase susceptibility to disease (Henjum and others 1994, Rhodes and others 1994). For example, increased exposure to sunlight can stimulate algal growth which may provide more food for fish; but if the temperature exceeds the range of efficient metabolism, growth rates are reduced (Petersen and others 1992).

Stream temperature may also impact substrate, indirectly. Stream temperature is inversely related to water viscosity. Cooler, denser water can hold more sediment in transport and may reduce the fine sediment loading of gravel used for spawning (Heede and Rinne 1990).

Beschta and others (1987) describe the interaction between landscape characteristics and stream temperature. The routing of water flow (surface versus subsurface) impacts the temperature of water entering a channel. Subsurface flow reflects the temperature of the watershed's subsoil environment. In the stream, water temperature changes because of net radiation, evaporation, convection, conduction, and advection. Net radiation is the solar radiation that is absorbed by a stream surface. This is affected by topographic and vegetative shading and cloud cover. Albedo of the stream may also influence net radiation; a clear stream is a black body, and a turbid stream reflects solar radiation (Logan and Lammers 1966).

Heat gain or loss from evaporation depends on the vapor pressure gradient between the water surface and the air immediately above the surface. Convection, internal movement within a fluid because of differences in density or temperature, increases with increase in temperature gradient between the water surface and the air immediately above the surface. Wind speed at the air-water interface is also an important factor. Conduction of heat between the water in the stream and the streambed depends on the type and color of material that makes up the bed. A dark basalt absorbs more heat than a light granite. Bedrock channels are more efficient than gravel-bed channels at conducting heat.

The importance of groundwater to salmonids is also being recognized. Advection is the result of heat exchanges as tributaries or groundwater of different temperature mixes with the main streamflow. Areas of upwelling groundwater and aggraded floodplains were historically key production areas for salmon. Bedrock outcrops and encroaching canyon walls are often locations for groundwater discharge (Stanford and Ward 1992). Springs may also provide important cool water refugia (Bilby 1984). Channel characteristics and morphology also influence the amount of heat gain or loss of a stream. The surface area over which energy transfers take place is important; wide, shallow streams receive more solar energy than narrow, deep ones. Discharge is also significant in that for the same surface area and energy input, the temperature change expected of a high-discharge stream will be less than a low discharge stream.

Delineation of Landscape-Level Ecoregions

Data sources—The study area includes the Grande Ronde, Asotin, Tucannon, Imnaha, Walla Walla, Umatilla, Middle Fork, and North Fork John Day subbasins and the upper reaches of the mainstem John Day subbasin (fig. 5). Primary types of mapped information used to delineate landscape-level ecoregions were soil, historical and present-day vegetation, geology, topography, and climate. Because the quality of the landscape-level ecoregion map is partly a reflection of the quality of the source material, a detailed description of each source along with an assessment of its quality and its utility to the delineation process is provided in the discussion of each landscape characteristic. Table 5 summarizes the source maps used in the delineation process.

Data integration—Ecoregion lines were drawn using a synthesis of digital layers, maps, and descriptive information. We used topographic maps as a base because: (1) frequently the other landscape characteristics follow topography and (2) these maps are readily available and meet National Map Accuracy Standards (GS 1989). A GIS was useful for easily combining map units into groups that we felt were important for stream habitat and plotting maps at our working scale of 1:100,000. For each available digital layer, 1:100,000-scale color plots were made to overlay the 1:100,000 scale topographic quadrangles. Lines from each plot were color-coded by landscape characteristic and transferred to clear mylar. Each topographic quadrangle had a mylar sheet for vegetation, geology, and soil. A blank sheet of mylar was used to sketch ecoregion lines.

Topographic maps along with the mylar overlays of soil, geology, and vegetation were overlain singly and in combinations on a light table. Placement of ecoregion lines was based upon knowledge of how landscape characteristics might influence stream habitat. Location of landscape characteristics on nondigital maps of differing scales and written descriptions were visually estimated and this information was also used in the delineation process. Greater emphasis was placed on maps of higher quality and better resolution. Lines were not determined by overlaying source maps within a GIS because of: (1) lack of necessary information in GIS format; (2) differences in quality, scale, and resolution of the source maps; (3) use of nondigital maps; (4) use of descriptive information; (5) spatial differences in importance of the properties of each of the landscape characteristics; and (6) differences in importance of each of the landscape properties in influencing stream habitat. Further discussion of the methodology can be found in Bryce and Clarke (1996), Clarke and others (1991), Gallant and others (1989), and Omernik (1987, 1995).

After delineating approximate boundaries for landscape-level ecoregions from all available map and textual sources, we evaluated the boundaries. The first set of draft lines were transferred to a plastic-coated 1:100,000 scale topographic map for use in the field. Approximately 3 weeks of road surveys were conducted to evaluate the lines and questionable areas. Slides and a video were obtained for later use in the lab. In addition, local biologists, geologists, and soil scientists were contacted to assist in making boundary determinations in specific areas.

Map production—As a result of this field evaluation, some lines were redefined on the original mylar copy, and all lines were digitized into an ARC/INFO coverage. After digitizing, plots were made for each of the 1:100,000 scale topographic maps. Lines were reassessed by comparing them to the individual maps of landscape characteristics and checked for accuracy of labels and line digitizing. As a result of this step, changes were made to the digital map.

A map of landscape-level ecoregions was produced for seven contiguous watersheds within the Blue Mountain and Columbia Plateau ecoregions (fig. 6). The map depicted three levels in the ecoregion hierarchy—ecoregions, subregions, and landscape-level ecoregions.

Each landscape-level ecoregion differed from the adjoining region in one or more of four landscape characteristics: topography, soil, vegetation, or geology. A short, descriptive name was developed for each landscape-level ecoregion based on the defining landscape characteristics. Every map unit was color-coded and given a label corresponding to the name in the legend. For example, *pag* refers to a unit named ponderosa pine argillite. Our smallest map unit was 0.5 square kilometer (.2 sq mi), and because landscape-level ecoregions were sometimes discontinuous, the smallest landscape-level ecoregion was 2.6 square kilometers (1 sq mi). In describing each of the landscape characteristics, this label identifies the map unit associated with that characteristic. For example, when describing the areas of argillite, the map units containing *ag* may be either *pag* or *tag*; ponderosa pine argillite or true fir argillite, respectively. Usually a landscape-level ecoregion occurred within one subregion; but in specific cases, it may have may occurred within additional subregions as well. For example, most of the regions comprised of true fir forests are located within the Mesic

Forest Subregion. However, small disjunct patches of true fir also occur in lower-elevation subregions. These areas were too small to be mapped as subregions but were large enough to be defined at the landscape-level ecoregion scale.

Landscape characteristics—Individual landscape characteristics rarely (or perhaps never) independently influence stream habitat, although dominance may vary spatially. The type and magnitude of influence also varies spatially. This spatial diversity of influence is why we defined ecoregions based upon multiple landscape characteristics. However, the prediction of stream-habitat characteristics based upon the stream's location within an ecoregion is impossible for several reasons. First, we lack the scientific knowledge to relate an individual landscape characteristic type directly to a particular stream habitat characteristic. Also, landscape characteristics generally are mapped as discrete units, although in reality they occur as a continuum. Individual properties may combine to moderate or increase an effect, usually not in a direct 1:1 relationship. Finally the characteristics of the land adjacent to the stream, in concert with upslope characteristics and upstream influences, work to determine the characteristics of the stream.

We make no pretense that by using landscape-level ecoregions we can somehow predict the stream-habitat characteristics of an individual stream within any delineated landscape-level ecoregion. However stream-habitat characteristics are influenced by landscape characteristics and landscape-level ecoregions are delineated using landscape characteristics, so it follows that stream-habitat characteristics may be related to landscape-level ecoregions. In an attempt to elucidate the connection between landscape-level ecoregions and stream habitat, the relationships between each of the landscape characteristics and stream habitat are discussed. Discussion of geology/geomorphology and vegetation is by individual types and discussion of climate and soil is by properties.

Climate—Climate is predominantly influenced by elevation, aspect, availability of moisture, and the prevailing wind direction. In turn, climate greatly influences vegetation, soil forming processes, and geomorphology. Every aspect of stream habitat is directly or indirectly affected by climate.

Climate is a very important landscape characteristic; however, developing meaningful classes for climate is difficult. As Daubenmire (1956) found out when trying to use climate classifications to explain patterns of vegetation, "the major finding of the study, [was that] none of the four universal classifications of climate tested has much phytogeographical significance in the area under consideration [eastern Washington and northern Idaho]." He suggested that because vegetation, soil, and climate are correlated in this area, they should be used to recognize the same landscape units. Because annual means of temperature and precipitation mask information on daily and monthly variability that is important to understanding vegetation patterns and erosional processes the few maps of annual precipitation that were available for the study area did not weigh heavily in our delineation process. As Daubenmire (1956) points out, "Ecologists have for some time been aware that annual means of temperature (and to a certain extent, precipitation also) are scarcely worth even the small amount of trouble involved in their calculation, ..."

For Oregon, an annual precipitation map developed by the Oregon Climate Service using PRISM (Precipitation-elevation Regressions on Independent Slopes Model) was available. This model attempts to correct for the lack of weather stations in mountainous areas (Taylor 1994). PRISM uses precipitation data collected from weather stations and a DEM to generate estimates of annual precipitation. Precipitation data came from two primary sources, NCDC cooperative stations and NRCS SNOTEL stations for the period 1961 to 1990. Two terrain grids were used with 2.5 and 5 minute latitude/longitude terrain elevations. The 5 min (approximately 6 x 8 km per grid cell) was better able to resolve orographic effects (Taylor 1994).

For Washington, we used several maps from the State of Washington, Department of Natural Resources. A very coarse-scale precipitation map (Miller and others 1973) was marginally useful; much more useful was a map showing rain-on-snow zones (Brunengo 1991). These zones generally corresponded to elevation.

Climate more than any other factor controls the rate and nature of weathering of parent material. In arid areas physical forces dominate weathering, decreasing the size of particles with relatively little change in composition (Brady 1990). Precipitation increases with elevation and changes physical form while temperature decreases. A snow-dominated area is more likely to experience flooding because of either an early spring thaw or a rain-on-snow event. Increased precipitation directly effects the water quantity. Water is the primary mechanism for transporting substances within and from forested lands (Gill 1994). Erosion may be increased by higher precipitation, runoff, or stream discharge. The erosional effects of higher precipitation may be mitigated by increased vegetation and concurrent increased infiltration and storage capacity of soils.

Topography has a major influence on climate in this area. The Rocky Mountains block this region from the continental air masses moving from the east (Franklin and Dryness 1988) and the Cascade Mountains partially block the maritime influence of the Pacific Ocean. Precipitation falls mainly in the winter months, although local thunderstorms are common in the summer. Most of the precipitation in winter falls as snow in the higher elevations. Rain-on-snow is common in the lower elevations. Summers are dry and hot, and the winters are comparatively mild for this latitude, although not as mild as winters west of the Cascade Mountains. Climate in the Blue Mountains is noticeably different from the climate in the Columbia Plateau.

The Columbia Plateau is dry; precipitation increases as elevation increases. In the western part of the Columbia Plateau, this precipitation pattern forms a roughly concentric circle (Franklin and Dryness 1988). The lowest elevations, closest to the Columbia River receive about 10 to 23 centimeters (4 to 9 in) per year, increasing up to 40 to 60 centimeters (16 to 24 in) in the foothills of the Blue Mountains. Prevailing winds are from the west or southwest, which causes the western slopes of the

Columbia Plateau to be influenced by the maritime air funneling through the Columbia River gorge. Eastern slopes are drier because they are in the rain shadow formed by the Blue Mountains (Gentry 1991).

The diverse topography in the Blue Mountains influences local climate (Johnson and Clausnitzer 1992). Generally cooler temperatures are found as elevation increases. However, many valleys are colder than the lower slopes of the adjacent mountains because of cold air drainage. The maritime-influenced portions of the Blue Mountains have greater cloudiness, increased precipitation, higher relative humidity, and fewer fluctuations in winter temperature (Johnson and Clausnitzer 1992). Most of the Blue Mountains, except for the John Day basin, are influenced somewhat by the maritime climate.

The John Day basin is influenced less by the maritime climate and is in the rainshadow formed by the Cascade Mountains. Light precipitation, low relative humidity, rapid evaporation, abundant sunshine, and wide temperature and precipitation fluctuations characterize this region (Johnson and Clausnitzer 1992). Here the temperature in the winter is much colder and precipitation ranges from 25 to 51 centimeters (10 to 20 in) in the grasslands to 43 to 76 centimeters (17 to 30 in) in the higher forested elevations (Dyksterhuis 1981).

Soil—The importance of soil characteristics to stream habitat is not completely reflected in the mapping of landscape-level ecoregions. At the time of the mapping, readily useable soil information was lacking.

The State Soil Geographic Data Base (STATSGO) was obtained from the USDA Soil Conservation Service (SCS)[6] for Oregon and Washington (SCS 1993). This digital map and database were compiled from detailed soil survey maps and data on geology, topography, vegetation, climate, and Landsat images. On a STATSGO map, each map unit contains up to 21 components for which there are attribute data, but there is no visible distinction as to the geographic location of these separate components within the map unit. However, the percentage of each component is given, which was useful for our project. For each component, we looked at drainage, surface texture, permeability, and depth to bedrock. Within each component, data are provided for each soil layer. We looked at erodibility, percentage clay and organic matter, and top-layer depth for the top layer of each component. With this information, we derived a rough assessment of each map unit.

STATSGO data were too general for this project, and county and forest soil surveys were too detailed. If the county and forest surveys had been compatible and available digitally, we could have reclassified the data and made them more useful for our project. The lack of digital versions with an accompanying database was problematic; besides not allowing for reclassification, maps could not be produced at our working scale of 1:100,000. We located soil polygons using many individual map sheets, usually bound in a book, with descriptive information located on other pages. This was an error-prone and laborious method that was used mainly in the lower elevation agricultural areas, where soils played a more dominant role and there were questions raised from the other data sources.

The National Forest Soil Resource Inventories (SRI) delineate soils on high-elevation aerial photographs. For our purposes, the maps are too detailed. Each National Forest has one or more SRI books with maps and soil descriptions. For each map unit information is provided on plant community types, physiographic position, geologic materials, aspect, slope, present erosion, major drainage dissection, ground cover, overstory and understory vegetation, rock outcrops, estimated water holding capacity, erosion, and hydrology.

County soil surveys delineate soil phases, which are generally subdivisions of a soil series based on surface layer texture or slope. A soil series is defined as a group of soils having horizons similar in differentiating characteristics and arrangements in the soil profile (Soil Conservation Society of America 1982). Each soil phase is described in the county soil survey. From these descriptions, we obtained information on depth to bedrock, drainage, parent material, topographic position, potential natural vegetation communities, land use, and ranges for precipitation, air temperature, slope, and elevation. These maps also used aerial photographs as a mapping base. Most of these photos have not been rectified which made input into a GIS a major task.

Although the science of soil classification is fairly sophisticated, the hierarchical scheme was difficult to use. We found the most useful level of information was the soil series. However using soil series has several drawbacks: (1) the U.S. Forest Service's SRI do not use the soil series names; (2) individual landscape-level ecoregions were frequently comprised of several to many soil series; (3) soil series' names are not common knowledge, (e.g., Athena soils would not convey deep loess soils to most people unless familiar with the soils of the area); and (4) some of the soil characteristics important to stream habitat (i.e., texture and slope) may not be reflected until the next lower level in the soil classification hierarchy, the soil phase. However, using soil descriptions, much useful information can be learned which may influence stream habitat.

Ideally, we would like to have uniform digital coverage of soils at a scale of 1:100,000 or finer with an accompanying database reflecting soil characteristics for each polygon. This type of soil data would have allowed us to aggregate polygons on the basis of the characteristics we felt were most important in influencing stream-habitat characteristics. Both the Natural Resource Conservation Service, NRCS, and the U.S. Forest Service are heading in this direction. In addition to being difficult to work with, the available information is difficult to discuss in terms of importance of the different soil classes to stream habitat.

For these reasons, we chose to describe the properties of soil on the basis of importance to stream habitat rather than describing individual soil types. Due to the interrelationship of soil and vegetation, soil is discussed to some extent in the vegetation section. For people familiar with the soils of the area, table 6 provides a list of the dominant soil series associated with most of the grassland map units. The soil series names were listed only for grassland map units because soil was frequently a dominant characteristic of these map units, and the National Forest SRI's do not use soil series names. Interpretation of soil characteristics can be improved with the availability of finer-scale uniform digital soil data.

The properties of soils that we thought to be the most important in influencing stream habitat were: texture, depth-to-bedrock or other impermeable layer, drainage, permeability, porosity, percent clay, percent coarse fragments, percent organic matter, erodibility, and parent material. The effect of parent material on soil will also be discussed in the section on geology. Harvey and others (1994) report a comparison of a few physical properties for surface layers of ash-, sandstone-, and basalt-derived soils in Eastern Oregon and Washington (table 7).

Texture, the relative proportion of sand, silt, and clay in a soil, is an index of the percentage of voids and the amount of water that can be held. Drainage is measured by the frequency and duration of periods when the soil is free from saturation with water. Permeability is the ease with which gases, liquids, or plants roots penetrate or pass though a layer of soil. In soils, permeability and porosity may be inversely related. Many sands and gravels have a lower porosity than clay, good drainage and aeration, but may be drought-prone. Silt is essentially microsand particles and usually has an adhering film of clay. Silt soils possess some plasticity, cohesion and absorptive capacity, but less than clay. Most clay, when wet, is sticky and plastic, which makes it cohesive. Clay soil is fine textured and has slow air and water movement, giving it a high porosity and low permeability. Gravels have high permeability, but the porosity differs based on the amount of sorting. Unsorted gravels have low porosity and sorted gravels have high porosity. Gregory and Walling (1973) report average ranges for porosity and permeability (table 8).

Clay because of its high cohesion and sand because of its high permeability is less water erodible than soils with mostly silt. Because of low cohesion, sand is easily eroded by wind; and on steep slopes, it is prone to dry ravel and erosion by sheetflow where vegetation is minimal. High amounts of organic matter and coarse rock fragments decrease the susceptibility of any soil to erosion.

Drainage reflects texture, depth to bedrock or other impermeable layer, and slope. Poorly drained soil is commonly found in old lake basins, alluvial deposits, and mountain meadows where the soil contains organic matter, clay and/or silt, and there is little slope. In these areas, streams are slow and meandering with pool habitat in the meander bends. Substrate is usually composed of fine materials. The water table is generally high and water seeps slowly into the streams. Alluvial deposits can also be excessively drained along with terraces and other areas with sandy or gravelly soil. These areas usually contain few perennial streams.

Johnson and Clausnitzer (1992) classify soils in the Blue and Ochoco Mountains in the following broad categories: (1) residual-derived in place from predominately bedrock or colluvial rock materials; (2) ash/loess-derived from deposited and accumulated ash and/or loess over older buried soil material; and (3) mixed-derived from colluvium, ash, and/or loess mixed well in surface layers over buried soil material. Residual soil differs from volcanic ash and loessial soil in several respects; it has (1) finer textured in the upper profile, (2) increased structure, (3) higher coarse fragments, (4) lower water-holding capacity, and (5) higher bulk densities. Ash soils have (1) high water holding capacity, (2) high water infiltration rates, (3) low compactability, (4) little particle cohesiveness, and (5) disproportionately high amounts of nutrients in upper surface layers. Loessial soil (1) is normally high in base saturation (can hold a large amount of nutrients, (2) has high content of weathered minerals and is thus high in nutrient reserve, and (3) generally has excellent physical properties. Productivity of plant communities is closely related to the ash and loess content of the soil. Hall (1973a) tabulated the stocking in trees per acre at 6 in average diameter at breast height with 10 rings per inch growth for mixed conifer with residual soil to be 275 to 330 versus 340 to 395 for mixed conifer with ash soil. Because southern and southwesterly slopes were exposed to the prevailing wind in the Blue Mountains, the deposits of loess were shallower. Also, the loess came from the north, so the south-facing slopes were sheltered from the deposits. Under some conditions, ash soils support good vegetation cover that protects the ash from erosion (Johnson and Clausnitzer 1992). However, the development of soil in the thick ash deposits of the John Day formation was hampered by lack of moisture. Lack of soil development and moisture increased erodibility and hampered vegetative cover. Lack of vegetation in turn contributed to increased erosion and lack of soil development. Lack of moisture seems to be the key factor in this positive feedback.

Vegetation—Vegetation is the most dynamic of all the landscape characteristics used to define landscape-level ecoregions. Johnson and others (1994) state that "the vegetation of eastside Washington and Oregon has a long history of natural disturbance." Fire, grazing and browsing by ungulates, insect outbreaks and disease epidemics, windthrow, flooding, and erosion have enhanced biodiversity. Management-induced disturbances have modified the natural order in ways both complimentary and detrimental to eastside ecosystems (Johnson and others 1994).

Because vegetation is dynamically influenced by both natural and anthropomorphic disturbances, vegetation classifications and maps vary widely. An assessment of the advantages and limitations of the existing vegetation classifications and maps to the goal of the project was essential. The goal of this project was to define landscape-level ecoregions as a tool to better understand the potential capacity of streams. To utilize the best available information, we kept in mind the characteristics of vegetation that may influence a stream's potential capacity. Ideally, we were interested in obtaining a classification of vegetation that factored in the role of natural disturbance, while acknowledging that it was extremely difficult or perhaps impossible to tease apart natural from anthropomorphic disturbance, especially with the issues of fire and grazing.

Vegetation directly influences stream habitat by providing shade and large woody debris and other organic matter to the stream. Vegetation influences erodibility, which in turn influences substrate and habitat complexity. Vegetation also serves as a climatic indicator, providing valuable clues to moisture and temperature regimes (Woodward 1987). The amount and importance of precipitation, interception, transpiration, infiltration, and runoff varies considerably between forest types (Gill 1994). Differences in soil, climate, and vegetation density all contribute to this variation.

There is a general trend to increased tree stocking with increased elevation, peaking with the true fir. Hall has recorded tree stocking ranges in the Blue Mountains (table 9).

The ponderosa pine/grassland areas have the lowest stocking, and the true fir has the highest, although the range is quite variable. The vegetation density of an area affects sensitivity to erosion, stream temperature, and snow melt. For western forests, Franklin (1992) found that old-growth forests intercept a large portion of the snow. The intercepted snow either melts and drips to the ground or is lost to sublimation and evaporation. In cutover lands, deeper accumulations of snow occur and melting occurs more rapidly because wind speed and turbulence at the snow surface are higher. We speculated that the same principle may hold true for closed canopy versus more open canopy forests, although snow depth would be less for the lower elevation forests.

Soil organic matter plays a role in soil-water availability, nutrient cycling, and erosion control (Harvey and others 1994) In lower elevation vegetation zones, the nutrient rich surface layer is usually washed away. Lower site productivity from reduced nutrients coupled with a drier moisture regime results in a lower soil organic content. Generally, soil organic content is highest in the moister zone of true fir and lower in the drier zone of ponderosa pine. Buckhouse and Gaither (1982) found in a study of sediment losses from ten natural ecosystems that meadow and forested ecosystems were statistically similar and that losses for grassland, sagebrush, and juniper were significantly higher than the meadow and forested ecosystem.

The vegetation information used to define landscape-level ecoregions was a synthesis of available information. Each piece of information had its utility and its limitations. The concept of potential natural vegetation (PNV) was the most useful for this project, attempting to map vegetation as it might appear if humans were removed from the landscape. However, the only available PNV map of the area was Kuchler's map of the United States at 1:7,500,000 scale (GS 1970), which was too general for our purpose.

The concept of plant associations was theoretically useful. If a stand of vegetation is able to develop and persist in its environment, and if the competitive forces are without major disturbing influences, then following a relatively long period of time those plants capable of reproducing in competition will constitute the "climax community." The unit of classification based on the probable, or projected, climax community type is defined as the "plant association" (Johnson and Clausnitzer 1992). Hall (1973a, 1973b), Johnson and Clausnitzer (1992), and Johnson and Simon (1987) have produced thorough handbooks on the plant associations of the Blue Mountains. Their descriptions of plant associations were informative and provided some information useful in making boundary decisions. However, very small-scale dot maps were frequently the only spatial information found in plant association reports. These dot maps gave approximate locations where certain plant associations were found. This type of mapping was inadequate for our purposes. In addition, much of the work in forested communities (Hall 1973a, 1973b; Johnson and Clausnitzer 1992; Johnson and Simon 1987), was limited to Forest Service land and did not include private land.

Consequently, we chose to map the forested vegetation from historic forest maps rather than use plant associations. We assumed that these historic maps reflected a condition less-impacted than present day, especially in the higher-elevation forested areas These maps also showed the results of disturbances such as fire, logging, and grazing. Historic forest county maps were digitized by the Region VI, USDA Forest Service (PNFES 1949, 1952, 1957). The original maps were at a scale of 1:63,360. The counties and original date of mapping included:

Oregon		Washington	
County	Date	County	Date
Union	1958	Asotin	1935
Umatilla	1958	Columbia	1935

Wallowa	1957	Garfield	1935
Grant	1960		
Wheeler	1953		
Crook	1952		
Baker	1957		

These county forest maps were very helpful. In addition to these digital maps, two paper maps, Forest Type Map of Oregon and Forest Type Map of Washington at a scale of approximately 1:250,000, were used (Andrews and Cowlin 1936a, 1936b; PNFES 1936). Both of these surveys were a result of Section 9 of the McSweeney-McNary Research Act of 1928, which called for a comprehensive and detailed investigation of the existing timber resources by volume and area. The surveys used all existing information on distribution of forest types and made type maps of all forest areas in the region for which no usable data existed (PNFES 1936, 1949, 1952, 1957).

The digital forest maps by county were easier to use because they could be plotted at our mapping scale of 1:100,000. We thought that they might contain more accurate information being newer and more detailed than the Andrews and Cowlin maps. However, the Andrews and Cowlin maps represented a less human-impacted condition in the forested areas. In many places, logging was confined to the lower elevations until the 1950s (Oliver and others 1994). Because of registration difficulties with the 1936 maps, we adjusted some lines using elevation and aspect information from the literature.

Literature about the vegetation communities (Franklin and Dyrness 1988; Gannett 1902; Hall 1973a, 1973b; Johnson and others 1994; Johnson and Clausnitzer 1992; Johnson and Simon 1987; Munger 1917) was used to resolve conflicts between the two maps. For example, juniper has increased its range partly because of fire suppression. This was very evident in comparing the 1930s and 1950s mapping. In this case, we used the 1936 map to define the juniper areas. We knew that the moister ponderosa-pine-dominated sites are often grand-fir-climax sites that historically were maintained by frequent low intensity ground fires (Hall 1991, Lehmkuhl and others 1994). Johnson and Clausnitzer's *Plant Associations of the Blue and Ochoco Mountains* (1992) describes these areas as grand fir plant associations and provides the early seral role of ponderosa pine in the section titled "Successional Relationships." These areas were delineated as ponderosa pine on the landscape-level ecoregion map because we intended our mapping to reflect the role of fire as a natural disturbance. Johnson and others (1994) state that "throughout the presettlement period, fire was an integral part of the maintenance and function for the majority of eastside ecosystems."

The intent of the 1936 map was to map timber resources, therefore, the extent of subalpine fir forests was unimportant. Subalpine fir was mapped with noncommercial rocky areas on the 1936 maps. This mapping convention caused some difficulties for us. Fortunately in the accompanying forest statistics for each county (Bolles 1937; Buell 1937; Litchfield 1937; Moravets 1937; Pelto 1937; Sankela 1937a, 1937b; Wolfe 1937), they did not lump these two categories together. We used these numbers and the later forest mapping to evaluate and adjust our map delineations.

The Oregon Actual Vegetation digital map and manual (Kagan and Caicco 1992), developed as part of the Oregon Gap Analysis Program, was marginally useful because it represented actual conditions after decades of land use and vegetation conversion Mainly it was used for additional information when large patches of larch, Douglas-fir, lodgepole, or noncommercial rocky areas were in question. The map was compiled by visually photo-interpreting Landsat MSS false-color infrared positive prints. There were registration problems with this map, and it is being redone.

We defined five forest zones—Juniper, Ponderosa Pine, Douglas-Fir, True Fir, and Subalpine Fir. We felt that by using vegetation zones instead of a finer-scale classification, the variability caused by disturbance history was lessened. Table 10 lists the major species occurring in each forest zone and also gives an approximate elevation and annual precipitation range for each zone. The primary sources for the table and descriptions of each zone were Franklin and Dryness (1988), Hall (1973a, 1973b), Johnson and others (1994), Johnson and Clausnitzer (1992), and Johnson and Simon (1987). Only Franklin and Dryness (1988) provide information on seral and climax forest species composition. The table is intended only as a general guide to species composition.

Vegetation in the study area is greatly influenced by the presence or absence of marine influence. Elevation ranges given for most zones apply to the entire study area. Although zones will usually start higher in areas not maritime influenced. The maritime-influenced zone subregion (fig. 4) indicates the extent of maritime influence. Interfingering between contiguous forest zones is also important in this area. Certain zones extend further into dry climates by taking advantage of north-facing slopes and stream margins and ascend farther on exposed slopes and ridges. The presence of deep soil with high moisture holding capacity, such as formed from ash, also allows vegetation to extend into areas with less precipitation.

Occupying the zone between the ponderosa pine and the grassland or sagebrush zones was the western juniper zone (map units beginning with *j*). This zone only occurred in the John Day basin of our study area, perhaps because of continental influence. This is the driest "forested" zone with most of the precipitation falling during the winter. Soil is typically light-colored, coarse-textured sandy loam, and low in organic matter.

Ponderosa pine is climax vegetation on the warmest and driest forest sites and is a major seral component in the Douglas-fir and grand fir series. Our ponderosa pine zone contained both climax and seral ponderosa pine forests (map units beginning with *p*). The thick bark of ponderosa pine allows it to withstand ground fires better than the thin-barked true firs. Climax ponderosa pine forest occurs on coarse, sandy soils and where cracks in the bedrock permit trees to tap underlying moisture. Soils on these sites are usually dry at depths of 10 to 61 centimeters (4 to 24 in) for 60 or more consecutive days during summer and autumn. Ponderosa pine forests grow on three distinctive types of soil. The ash soil is coarse, but it has a high moisture-holding capacity. Organic matter is concentrated near the surface and declines rapidly with depth. Soil derived from basalt, andesite, and clayey sediments is moderately deep and dark-colored, fine and loamy. This soil is easily compacted and puddles when wet. Surface erosion is a problem on slopes greater than 30 percent. The soils most sensitive to erosion are derived from rhyolite, andesite, granitics, glacial till, and outwash. These soils are coarse, loamy, and shallow-to-deep with low organic matter content and low water-holding capacity. On cooler, moister sites the soil has more organic matter.

A mixed ponderosa pine/grassland or ponderosa pine/shrubland zone was identified (map units beginning with *m*) in areas at the lower edge of the ponderosa pine zone where the two zones intermix. In this area, ponderosa pine is confined to a fringe of trees along canyon sides, draws, and north-facing hillsides (Munger 1917). The geographic extent of this area (about 3500 square kilometers [1351 sq mi]) called for a new zone rather than dividing it between the ponderosa pine and grassland zones. A separate shrubland zone was not identified. Species for the shrubland component of the ponderosa pine/shrubland zone are found in table 11.

A Douglas-fir zone is identified by some authors (Hall 1973, Harvey and others 1994, Johnson and others 1994, Johnson and Clausnitzer 1992, Johnson and Simon 1987). Franklin and Dyrness (1988) say that its occurrence is conjectural except in parts of the Wallowa Mountains. Because of its wide ecological aptitude, Douglas-fir occurs in both the ponderosa pine and true fir zone; and it was difficult to differentiate based on the available maps. For this reason, we only delineated a Douglas-fir zone in the Wallowa Mountains (map units beginning with *d*).

The upper elevational limit of the ponderosa pine gives way abruptly to a very different, much denser stand of other species (Munger 1917) comprising the true fir zone (map units beginning with *t*). This zone included both grand fir (found in the northeastern part of the study area) and white fir (found further south). Franklin and Dryness (1988) treat these areas similarly because "these two species and the zones they typify occupy analogous positions synecologically and environmentally in their respective areas." To denote both white fir and grand fir in the name, we used the term "true fir." We recognized that subalpine fir is also a "true fir." However, because subalpine fir occupies a higher elevation and colder environment, we mapped it separately from our "true fir" category. The true fir zone is characterized by neither temperature nor moisture extremes. It is wetter and cooler than the ponderosa pine zone and has higher temperatures and less accumulation of snow than the subalpine fir zone. Soil is usually moderately deep because of the accumulation of volcanic ash. These soils are very fertile with rapid infiltration, high water-storage capacities, and good aeration.

The subalpine fir zone is the coolest and moistest forest zone with a deep winter snowpack (map unit beginning with *s*). Subalpine fir forests may be found below this elevational range in frost pockets and areas affected by cold air drainage, such as glaciated valley bottoms. Soils are coarse and stony with well developed, relatively thin humus layers, and low fertility. They are erodible when exposed to wind. Our subalpine fir zone contained a whitebark pine zone analogous to the juniper zone at the lower forest fringe.

Information on vegetation in lower elevation, nonforested land was critically lacking for this project. Historical forest maps only showed areas outside the forested areas as "nonforested." The map of Actual Vegetation of Oregon (Kagan and Caicco 1992) was of little help because much of this area is in agriculture now. Potential-vegetation community descriptions from the county's soil surveys were helpful. Differentiation between grass and sagebrush zones was sometimes difficult, especially in the Pleistocene Lake Basin Subregion. Differentiation within these classes was not possible with the mapped information available. However, many of these finer vegetation classes are expected to follow other mapped landscape characteristics, particularly differences in soil depth and moisture. Literature on nonforested vegetation was obtained from Daubenmire (1988), Franklin and Dyrness (1988), Johnson and Simon (1987), and county soil surveys.

We divided the nonforested vegetation into zones starting with the warmest and driest: aridic grassland, sagebrush, grassland, and alpine. The choice of these classes was based partly on the review of the scientific literature; greatly influencing the decisions was the availability of spatial data. The distinction among rigid, low, and big sagebrushes and between grassland communities dominated by fescue and those that are not would have been valuable for determination of soil depth and moisture regime;

however, maps showing these distinctions are not commonly available. Table 11 shows the dominant species occurring in these zones. The primary sources for the table and descriptions of each zone were Daubenmire 1988; Dyksterhuis 1981; Franklin and Dryness 1988; Hall 1973a, 1973b; Harrison and others 1962, 1973; Hosler 1983; Johnson and others 1988; Johnson and others 1994; and Johnson and Clausnitzer 1992. The table is intended only as a general guide to species composition.

The driest zone was the aridic grassland which occurred mainly in glaciofluviate deposits (map units beginning with *g* and containing *go/t, es, gfg, aca, loda/h, and gfs*). The mean annual precipitation in this zone is usually less than 30 centimeters per year (12 in per yr).

The next driest zone, which we called the sagebrush zone, consists dominantly of big sagebrush and bluebunch-wheatgrass (map units beginning with *s*). Even in the driest part of this zone, there is virtually no bare ground in the undisturbed climax (Daubenmire 1988). Soil is mostly loam or stony loam. In the John Day basin, the sagebrush zone frequently abuts the juniper or ponderosa pine forested zones, possibly due to the influence of the colder, drier continental climate.

The grassland zone (map unit beginning with *g*) rises to an elevation of about 900 meters (2953 ft). This zone is wetter than the sagebrush zone. Most of the Columbia Plateau and some basins within the Blue Mountains are dominated by grassland communities. This zone could be broken into the mesic grasslands where Idaho fescue forms the climax communities and the xeric grasslands where Idaho fescue is absent and bluebunch-wheatgrass dominates if maps to show this distinction were available for the study area. Table 11 gives the species composition for these two grassland zones. The wetter grasslands areas are found at upper canyon elevations and on north-facing aspects at lower elevations and on deeper soils of the ridges where moisture is retained longer into the summer drought period.

The alpine zone included the alpine sagebrush and green fescue in the high Wallowas and alpine fescue communities in the Blue Mountains (map units containing *a*). The elevation ranges from 1859 to 2499 meters (6100 to 8200 ft). This zone was large enough to be mapped only in the Wallowa Mountains. On the granitic soils, rapid drainage leads to low vegetative productivity making this zone more erosive; on lava soils, there is more herbage, so erosion is less.

Geology and geomorphology—Geology and geomorphology play a strong role in controlling stream habitat characteristics, especially substrate, habitat complexity, and water quantity. Most geology maps are based upon rock type and age and mapping units may incorporate rocks with vastly different engineering or hydrologic properties. These groupings may be due to different mapping goals, units that are too complex to map lithologies, and/or map scale and resolution. Engineering and hydrologic properties such as joint structure, stratigraphy, erodibility, porosity, and permeability were more important for our purposes making it necessary to interpret geology maps for relevance to fishery biology and stream ecology.

A 1:500,000 scale geology map (Walker and Macleod 1991) of the State of Oregon, available in digital form, was useful. The map was originally produced at 1:250,000 and later reduced to 1:500,000. For the purposes of this project, the detail of the map was adequate. However, we recognized that this map was not intended to be plotted at the 1:100,000 scale of this project. Lacking other economically feasible options, we used the map and made adjustments along the way. The most noticeable problem was poor registration, especially seen in the alluvial areas. When working with the geology layer, each 1:100,000 map sheet was manually reregistered to place the alluvial areas next to rivers, requiring about a 1- to 2-centimeter (.39 to .78 in) shift in both the x and y direction. A draft geology map of southeast Washington (Johnson and Derkey 1993) was available in digital form although it was very coarse scale. Many local 1:24,000- to 1:250,000-scale maps were used to adjust the lines and resolve questionable areas.

Geologic mapping relies on topographic maps as their base (Weissenborn 1969), because geology is not usually a surface phenomenon. We frequently used topography to adjust our lines where it was evident that geology would follow a topographic feature. We used many reports on geology (Baker and others 1991; Barrash and others 1980; Bishop 1994; Bishop and others 1992; Brooks 1979; Ferns 1985; Gonthier and Bolke 1993; Hampton and Brown 1964; Hodge 1942; Hogenson 1964; Merriam 1901; Newcomb 1965; Oles and Enlows 1971; Orr and others 1992;

Reidel and Hooper 1989; Smith and others 1941; Taubeneck 1957; Thayer 1990; Walker 1990a, 1990b; Walker and Robinson 1990; Weissenborn 1969; Whiteman and others 1994; WRB 1963; WRD 1988) to help us understand the processes and potential topographic manifestations of the geology. In addition, these reports frequently had small schematic maps and descriptive information which was invaluable in delineating boundary lines and describing the geologic properties from which we could infer potential importance to stream-habitat characteristics. Using existing maps and literature, we have attempted to delineate and describe the characteristics of the rocks or formations that potentially influence stream habitat.

The hydrologic properties of a geologic formation are not determined solely by the permeability or porosity of a rock, but may reflect the joint structure (Gregory and Walling 1973). Stratigraphy also plays a large role in the movement of water through the bedrock. For example, basalt is not generally porous or permeable but it commonly has a hexagonal joint pattern that transmits water vertically and the Columbia River basalt frequently has extensive, lateral, permeable sedimentary deposits or paleosols between the flows. Both jointing and intrabeds contribute to the Columbia River basalts' importance in providing groundwater to streams.

Mineral composition strongly influences the weathering rate, soil productivity, and rate of erosion. The stratigraphy is important, for example, where the resistant basalt rests on top of highly erodible ash such as in the John Day formation. Focusing only on the top layer of basalt might mask the true erosiveness of the area. Stratigraphy at any single location is impossible to determine from maps where only the top layer of geology is mapped. The geomorphology of an area strongly influences the movement of water and erosion. Discussion of geomorphology is linked to both geology and topography.

The following section describes the major geologic types found in the study area and summarizes their origin, spatial extent, and properties relevant to stream habitat. In keeping with geologic convention, the units will be discussed in order of age. The pre-Cenozoic rocks include the metasedimentary and metavolcanic rocks associated with exotic island arcs, subduction and collision of the Pacific oceanic plate with the North American continental plate, and plutonic intrusions. These rocks outcrop in only about 10 to 15 percent of the Blue Mountains (Walker 1990b). The rocks of the Cenozoic Era are divided into the Tertiary and Quaternary Periods. The Tertiary Period was a time of major volcanic activity that formed the Clarno, John Day, Columbia River Basalt, and Strawberry formations. The Quaternary was a time of alpine glaciation and fluvial-generated alpine erosion with deposition of sediments in basins that shaped the current landscape of the study area.

Pre-Cenozoic Era—The pre-Cenozoic rocks (320 to 65 myr ago) are a direct result of plate tectonics. Brooks (1979) and Bishop (1994) discussed these pre-Cenozoic deposits. Most of Oregon and Washington were once part of the Pacific Ocean. The rocks exposed in Hells Canyon and in much of the higher elevations of Wallowas, Elkhorns, and old mountains in the region were formed as volcanic islands.

Sediments, including limestone, conglomerate, sandstones, and shales, accumulated from erosion of this island system, eventually burying the old volcanic rocks. The remnants of the old volcanic arc are called the Wallowa and Olds Ferry terranes, approximately 300 to 200 million years in age. (A terrane is a coherent package of rock built in one place through one kind of geologic process.) The subduction zone and portions of oceanic crust trapped and deformed between volcanic arcs is called the Baker terrane, and it is approximately 300 to 200 million years in age. The less-deformed package of sedimentary rocks that overlie the Baker terrane is called the Izee terrane, and it consists of shale and fine sandstone exposed in the Aldrich Mountains. As the terranes collided with the North American plate, older deeply buried and deformed volcanic rocks were heated and subjected to high pressure. Greenstones and sediments melted and rose into the surface of the overriding plate producing the granitic plutons that now form the core of the Wallowas and northern part of the Elkhorn Mountains.

The Baker terrane consists of argillite, chert, conglomerate, limestone, greenstone, sea-floor and island arc plutonic rock, high pressure schist and serpentinite from both crustal and supracrustal rocks that have been severely broken up, rearranged, and deformed. The crustal rocks are called a *melange* composed of ultramafic rocks, gabbro, quartz diorite, and albite granite severely deformed by folding and faulting. Melanges typically have a matrix of serpentinite, a scaly, slippery, green rock (map units containing *sp*). The largest exposures of these rocks are found in the Greenhorn, Elkhorn, Strawberry, and Aldrich Mountains and the Ochoco Mountains near Antone. The presence of serpentinite may increase the risk of landslides due to its slippery nature, lack of soil nutrients, and low vegetative productivity.

The Canyon Mountain complex in the Strawberry Mountains is considered island arc-related, not derived from ocean crust. In its uppermost sections, it consists mainly of gabbro, the coarse-grained equivalent of basalt. Gabbro weathers and erodes more rapidly than granitic rocks (Chesterman 1979) and like serpentine produces clays that are expandable, thus producing slide-prone soils.

Other lithologies common in the chaotic Baker terrane include ribbon chert and siliceous argillite—hard, silica-rich layers separated by thin, dark, fine-grained layers of shale (map units containing *ag*). This shale component makes the argillite erodible. These rocks are a major part of the Elkhorn and Greenhorn Mountains.

The sedimentary rocks in the Aldrich Mountains are composed of thick deposits of shales and very fine sandstones similar to the Elkhorn Ridge argillite except less metamorphosed—a composition that makes them more crumbly. These rocks are part of the Izee Terrane.

The Wallowa-Seven Devils Terrane consists of volcanic, plutonic, and sedimentary rocks that have been somewhat metamorphosed. The volcanic rocks were originally basalt, andesite, and dacite slightly metamorphosed to greenstone (map unit containing *vm*). The sedimentary rocks include shales and sandstone of the Hurwal formation and Lower sedimentary series as well as Martin Bridge Limestone composed of limestone deposited in shallow water and the Hurwal formation made up mostly of shale with some sandstone and a few conglomerates (map units containing *svm* and *se*). These rocks were best exposed in the northern Wallowa Mountains.

Large bodies of intrusive rocks called batholiths intruded the Baker and Wallowa-Seven Devils terranes. These rocks have the appearance of granite, but because they are rich in feldspar and contain little quartz, they are technically not true "granite." The name "granitic" or "granitoid" is more correct. The largest, the Wallowa batholith, is found in the core of the Wallowa Mountains. Other granitic intrusions include Bald Mountain and Battle Mountain and an unnamed stock along the John Day River near the Ritter Hot Springs. The intrusive rocks range from gabbro to granite, but feldspar-biotite-rich lithologies (tonalite and granodiorite) form the vast majority of the exposure. The intrusions formed contact halos where the surrounding rocks have been strongly foliated and metamorphosed (Weissenborn 1969). Erosion later stripped off most of the sedimentary rocks covering these intrusive rocks (Smith and others 1941). The surrounding sedimentary and volcanic rocks have been metamorphosed to varying degrees, which made it very difficult to generalize about their properties. These rocks are more resistant to erosion than they would be if unmetamorphosed. However, there is a wide range of erodibility for metamorphosed rocks depending upon degree of metamorphism and origin. Usually the metamorphic volcanic rocks (i.e., greenstone, metamorphosed basalt or gabbro) are resistant to erosion, while the metamorphosed sedimentary rocks (i.e., slate, metamorphosed shale) are not. The rocks classified as partly metamorphosed-sedimentary and volcanic rocks challenge even these generalizations. We colored the coded units containing metamorphic rocks similarly within vegetation zones but labeled them based upon the type of rock that was metamorphosed, i.e., *svm* for sedimentary and volcanic rocks partly metamorphosed, *sm* for sedimentary rocks partly metamorphosed, and *vm* for volcanic rocks partly metamorphosed.

Granitic outcrops are generally bold and well rounded (map units containing *in*). The rock is massive, tight and poorly permeable, and weathers to a coarse sandy rock waste (Hampton and Brown 1964). The abundance of minerals susceptible to chemical weathering (calcium plagioclase feldspars) and mechanical disaggregation (biotite) creates granular, friable, easily erodible soil and deep "grus." Megahan (1972) and Megahan and others (1992) have done several studies on the granitic rocks of the related Idaho batholith. They note that granitic soils in the western United States are noted for their high erodibility because of their relatively coarse texture, lack of cohesion, and occurrence on steep slopes. Their coarse texture accounts for the fact that most of their sediment loads are carried as bedload. Most of the streams in granitic areas are clear, only becoming slightly turbid during peak flows.

Cenozoic Era-Tertiary Period—Significant volcanism occurred during the Tertiary Period. The Clarno formation, approximately 50 to 35 million years in age, is a very thick sequence of andesite flows, mudflows, breccias, andesitic to rhyolitic volcaniclastic rocks, and tuffaceous sedimentary rocks. The Clarno formation is part of map units containing *cl* except the tuffaceous facies that is combined with other map units containing tuff—*tu*. The formation occupies a large area of more than 4000 square kilometers (2485 sq mi) to the south of the Blue Mountain uplift and near the western margin of the Blue Mountains ecoregion. A smaller area of about 400 square kilometers (248 sq mi) is found along the axis of the Blue Mountain uplift in southern Morrow county (Walker and Robinson 1990). The Clarno formation's bimodal geographic distribution, as well as its complexity and diversity of ages suggests that several different volcanic periods may be represented.[2] Rock types with different rates of weathering contribute to the unique terrain found in the Clarno formation. The volcaniclastic, sedimentary rocks in the Clarno formation show a much higher degree of induration than the younger, ash-rich, overlying John Day formation. Clarno mudflow (lahar) deposits frequently form steep bluffs ornamented frequently with balanced rocks (Merriam 1901). Topography developed on Clarno mudflows yields large, rough inclined surfaces, hogbacks, knobby hills, buttes, and V-shaped canyons. Resistant lavas are peeled off in layers because of the alternation of resistant lavas and yielding sediments. Although Hodge (1942) said that the Clarno formation is very resistant to erosion, some areas mapped as Clarno include andesite flows separated by tuff beds. Such areas are susceptible to landsliding. Because of the diversity of rock types, any generalization about the stability of the Clarno formation is probably inaccurate. In the headwaters of the Grande Ronde River, there is a large area mapped as andesite, dacite, and sedimentary rocks by Walker and MacLeod (1991) and Ferns and Taubeneck (1994). We mapped this unit with the Clarno formation due to similarity in rock types.

The John Day formation was laid down upon the eroded surface of the Clarno formation (map units containing *tu*). The John Day formation is very distinctive, and much has been written about it. It is an assemblage of tuffaceous sedimentary rocks, air fall and ash-flow tuff and sparse olivine-rich basalt lava flows (Robinson and others 1990). The John Day formation is restricted to the lowland areas of the John Day basin (Thayer 1990) and varies in depth from a few feet to more than 610 meters (2000 ft).

Landslides are common along the steep stream-cut slopes incised into the John Day formation and some are immense. Water flows through the heavy basalt that caps the John Day formation and soaks the tuffs below causing the basalt to slip, creep and landslide (Hodge 1942). Some of the largest landslides were mapped in map units containing *ls*. Except in basins, soil does not form on the John Day formation because it is so pervious to groundwater and blows away easily. Elephant-backs, gullied slopes, pinnacles, and badlands comprise the topography in these areas (Hodge 1942).

There were several other pockets of primarily tuffaceous sedimentary rocks in the study area. Although they may be different ages, structurally we considered them to be similar and have grouped them into map units containing *tu*. In the Grande Ronde basin, Hampton and Brown (1964) report that some tuffs contribute to the rich soils for which the upland district is famous. They note that the tuff weathers more rapidly than the basalt and occupies topographic depressions bordered by steep erosional escarpments.

The Columbia River Basalt Group (CRB) covers most of the Columbia Plateau and is the most widespread geologic type in the study area. It consists of layer upon layer of basalt flows which may be interspersed with extensive thin layers of sedimentary deposits or paleosols. The sedimentary layers and soil were deposited in the time between flows. In some places, these flows are more than 1524-meters (5000-ft) thick (Orr and others 1992).

The Columbia River Basalt Group (map units containing *cb*) is stratigraphically subdivided into the Saddle Mountain, Wanapum, Grande Ronde, Picture Gorge, and Imnaha Basalts (Walker and MacLeod 1991). Over 90 percent of the CRB are the Grande Ronde basalts, erupted between 15.5 and 19.5 million years ago. They are generally crystal-poor, silica-rich, fine-grained basalt (Reidel and Hooper 1989). Grande Ronde basalts are about 610 meters (2,000 ft) thick in the Grande Ronde valley (Bishop and others 1992). The Picture Gorge Basalt with high magnesium and rapid weathering is exposed in most of the John Day watershed. Because the Picture Gorge basalt tends to be less resistant to erosion and has a significant exposure in the study area, we delineated it as a separate category (map unit containing *pg*). Future work may find the difference in erosion to be negligible when compared to other geologic types, and it may prove meaningless to stream habitat.

Many basalt flows displayed a characteristic sequence of layers. The lower section was characterized by huge vertical six-sided prisms. These prisms have a large diameter at the base and become smaller near the top. They break at right angles, and breaks are more common near the tops of the flows. This characteristic fracture pattern produces large talus slopes of "brickbat" basalt. The tops of each flow are usually covered by a mantle of vesicular-to-scoriacious lava. The basalt is usually fine and even grained.

Basalt is not porous, but the porous and permeable tops of some flows, joint patterns, and incomplete closures of one flow over another make the Columbia River Basalt Group a very important aquifer (Hampton and Brown 1964, Hogenson 1964, Newcomb 1965, WRB 1963). Streams without sources outside the Columbia Plateau only flow in the summer where springs emerge from the basalt; usually along axis of synclines (Newcomb 1969). During low flow periods in the Upper Grande Ronde River basin, creeks draining the older metamorphic and intrusive rocks of the Elkhorn Range are dry, but creeks maintain a small, constant flow where the Columbia River Basalt overlies these older deposits (Hampton and Brown 1964).

In northern Wallowa and Union counties, there are some sedimentary beds interbedded with the Columbia River Basalt Group. These deposits were formed in shallow lakes and peat bogs that formed on tops of the flows (Ferns 1985). These deposits can be as much as 91-meters (300-ft) thick. They crop out at only one very limited and remote location. The presence of these lacustrine deposits beneath the basalt may make slopes more susceptible to landslides. For the time being, we have mapped them separately as map units containing *bl*.

Bowen's reaction series shows the sequence in the crystallization of a basaltic melt (Foster 1975). Olivine is the first mineral to crystallize as the temperature falls; quartz is the last. Conversely, olivine is the first to break down under chemical weathering which contributes to unstable clays. This helps explain the differences in volcanic rocks and associated soil. Basalt generally contains olivine; rhyolite contains quartz and is the extrusive equivalent of granite. Andesite falls between. Quartz is very resistant to weathering; olivine is not. So the minerals forming basalt are more erodible than the minerals forming rhyolite. Generalizations are difficult because the jointing structure plays a significant part in determining erodibility. Only a small portion of the study area in the southwestern corner contains significant amounts of rhyolitic rock (map units containing *rh*). Significant amounts of andesite are found in the study area.

The Strawberry Mountain andesite (map units containing *an*) is a product of volcanoes rather than the basalt floods that produced the Columbia River and Picture Gorge Basalt Groups. This platy andesite does not have the well developed vertical joint system of basalt. It has random vertical joints, not well developed, and thin, discontinuous horizontal joints instead. Because of this, the andesite is relatively impermeable and does not have the aquifer properties of the basalt (Hampton and Brown 1964). The platy structure of this andesite may make it more erodible than the surrounding basalt.[7,8]

Concurrent with the volcanism, tectonism played a major role in the formation and deposits of the basins in the area. Two types of basins were formed. The earliest basins were a result of synclinal downwarps in flow sequences of the Columbia River Basalt Group i.e., the Agency, Arlington, John Day, and Fox basins (Walker 1990a). The Ukiah basin is mapped by Walker (1990a) but not discussed and was probably formed by faulting as well as folding[2] in a structural depression. The southern extent of this basin was difficult to map. Soil and topographic maps showed the southern part to be similar to the area around Ukiah. However, the geology maps do not affirm this. The Arlington, Agency, and Ukiah basins contain partially cemented gravel and interbedded tuffaceous sand and silt (map units containing *ca*). The margins of the Ukiah basin are mapped in units containing *rca*. They have a thinner veneer of loess and include some residuum. The lower elevations of the Arlington basin and the Walla Walla basin are overlaid by thick layers of loess and glaciofluviate deposits, which will be discussed in the Cenozoic Era-Quaternary Period section. In the John Day basin, the present Strawberry and Aldrich Mountains were raised 2 to 3 kilometers (1.5 to 2 mi) above the valley floor by faulting along the John Day fault system. Clastic rocks and tuffs from the Strawberry Mountain volcanoes washed out over the basalt and produced the Mascall formation. Gravelly, sedimentary rocks from the rising mountains filled the John Day valley producing the distinctive Rattlesnake deposits (Thayer 1990, Walker 1990a). A prominent bed of welded tuff or ignimbrite is present in the upper part of the Rattlesnake formation (map unit containing *fs*). The Fox basin is a structural trough confined by faults and a syncline. It contains rhyolitic tuff and pebble gravels in the northwest and thin basalt flows faulted with tuffaceous beds in the south (map units containing *tu*).

The more persistent basins in this area are a result of faulting. The Yakima Folds, a series of anticlinal ridges and broad, flat-floored synclinal valleys and basins, influenced the formation of the Walla Walla basin. The Grande Ronde basin is a graben-containing, fine-grained, poorly drained lacustrine deposits (map units containing *la*). Where streams enter the basin bouldery alluvial-fan deposits occur (map units containing *af*). Along the edges of the fault scarp (map unit containing *fsc*) are the colluvial deposits (map units containing *co*). The Wallowa Mountains were uplifted by faulting on two sides causing their characteristic bowl shape and radial drainage pattern (Smith and others 1941). Glaciation coupled with this uplift caused the mountain streams to become deeply incised (Bishop 1994) and formed the Wallowa basin, Joseph Upland. There is also a colluvium slope along the southwestern edge of the basin.

Nonchannelized streams in the basins generally have a meandering pattern. The major differences within the basins are in the drainage properties. The areas underlain primarily by gravels such as the alluvial fans have good drainage. Areas underlain by cemented alluvium or fine silt have low permeability.

Extensive folding also influenced other areas. Major structures such as the Blue Mountain anticline and the Walla Walla and Umatilla synclines were formed. From Prairie City to Dayville, the John Day River flows in a synclinal trough (BR 1985), and the Grande Ronde River flows through a synclinal trough from Starkey to LaGrande (Hampton and Brown 1964). This latter area is intersected by many northwest striking faults (map unit containing *f/p*). The Columbia River Basalt Group in the Blue Mountains is the southern upwarped and deformed part of the anticline (Baker and others 1991). In these uplifted parts, streams have cut narrow, steep-walled canyons where the rock is resistant. These valleys are marked by the stair-step edges of the basalt layers. Several large upland areas remain undissected. Slopes on these plateaus are generally less than 15 percent; in the dissected canyons, slopes generally range from 30 to 60 percent.

In places where the basalt is thin or underlain by the John Day formation, much wider valleys are formed (Orr and others 1992). The basalt in the Columbia Plateau region is less deformed and underlies loess, lacustrine, and glaciofluviate deposits. However, these deposits have not modified the drainage pattern controlled largely by the surface of the underlying basalt. The stream gradients are generally high (greater than 50 ft per mi [15 m per km]), determined by the tilt of the basalt (Harrison and others 1962).

Cenozoic Era-Quaternary Period—Generally, except for the basin fills, the geologic deposits before this period have been indurated (consolidated and cemented). All the deposits in the Quaternary Period consist of unconsolidated deposits. They are not delineated on conventional bedrock geologic maps. These maps do not show quaternary deposits unless they are extensive, cover all bedrock units, or disrupt stratigraphy (as in a landslide). Gonthier and Bolke (1993) cite the mapping criterion of Swanson and others (1987) to map sediments wherever they are sufficiently thick to obscure the underlying basalt. The subjectivity of this statement makes it clear why geologic maps vary considerably in the portrayal of these deposits. For our purposes, we used geologic maps in conjunction with topographic maps to determine the location of map-unit boundaries.

Glaciation had both direct and indirect effects on the study area. During the early part of the Quaternary period, the Pleistocene epoch, alpine glaciation carved, eroded, and built morainal and fluvial deposits in the Wallowa, Elkhorn, Greenhorn, and Strawberry Mountains. Large amounts of sediment filled the Grande Ronde valley. Indirectly, flooding from glacial Lake Missoula was responsible for shaping most of the current landscape of the Columbia Plateau.

In the Strawberry Mountains, glaciers sculpted the principal valleys above 1524 meters (5000 ft) forming U shaped valleys (Thayer 1990). The radial valleys of the Wallowa Mountains were widened and deepened by these glaciers. Glacial deposits consisting of unsorted bouldery gravel, sand, and rock flour are found at the lower end of these valleys and adjacent lowlands (map units containing *gl*).

The highest floodwater from Lake Missoula reached almost 366 meters (1200 ft) (Bretz 1969). Backflooding left deposits in many nonglacial valleys of the Snake River such as the Tucannon and Asotin Rivers. Lake Lewis, formed by hydraulic damming behind the Wallula Gap is largely responsible for the features of the Walla Walla basin. Lake

Condon, formed from a constriction around the Dalles, strongly influenced the Umatilla basin. Hogenson (1964) described these deposits in the Umatilla basin and Newcomb (1965) described them for the Walla Walla basin. Glaciofluviate deposits are found below 229 meters (750 ft) (map units containing *es, gfg, and gfs*). This area has been scoured by wind and water, and the surface of these deposits is dotted by many blowouts. Deposits consist of undifferentiated gravel, sand, and silt. In the Walla Walla basin, these are called the Touchet Beds. Lacustrine deposits are found up to an elevation of about 350 meters (1150 ft). They have been severely dissected into long narrow ridges having steep north and east slopes and strongly sloping south slopes (Harrison and others 1962), consisting mostly of stratified lacustrine silt (map unit containing *ca*).

During these glacial periods, the weather was cold and windy, and vegetation was sparse, ideal conditions for wind erosion (Brady 1990). Consequently, extensive loess deposits blanketed the Columbia Plateau. These deposits are coarser and deeper near the source, the glacial lake beds. Map units were differentiated using depth and moisture in these loessial areas (map units containing *lo*), as discussed in the section on soil. In the dry areas with sparse vegetation, wind erosion is a major problem (Harrison and others 1962).

Although the recent alluvial valleys are relatively small (map units containing *al*), we have delineated them because of their importance to fish (Reeves 1988). These alluvial deposits consist of sorted and unsorted silt, sand, and gravel. The low gradient of these areas and the location of pools along the meanders makes them important refugia and rearing habitat for fish. Because of their depositional nature, they are subject to sedimentation from upstream sources. Where county soil surveys were available, we defined these areas relatively easily. In other areas, we relied upon their identification from the geology, actual vegetation, and STATSGO soil map. Often, their width was greatly exaggerated for cartographic purposes. We used topography to help us better refine the boundaries. Areas less than .3 kilometer (.2 mi) wide were not mapped. We expect that some small alluvial valleys were missed by this process.

Topography—The preceding sections have covered the characteristics of topography, therefore, this section only discusses the topographic maps and digital data used in this project. The components of topography; elevation, slope, and aspect are discussed in the sections on vegetation, climate, and soil. Because geomorphology is the science of topography, further discussion of topography are found in the section on geomorphology/geology.

We used 1:250,000 DEM's (Digital Elevation Models) for Oregon and Washington with a 60- x 90-meter (66- x 98-yd) resolution. Slope, aspect, and elevation were calculated from the DEM's. Slope was broken into 6 slope classes, aspect into 8, and elevation into 10. Slope classes were 0, 1 to 14, 15 to 29, 30 to 59, 60 to 89, and greater than 90 percent. Elevation classes were 0 to 300 (0 to 328), 300 to 600 (328 to 656), 600 to 900 (656 to 984), 900 to 1200 (984 to 1312), 1200 to 1500 (1312 to 1640), 1500 to 1800 (1640 to 1968), 1800 to 2100 (1968 to 2296), 2100 to 2400 (2296 to 2624), 2400 to 2700 (2624 to 2952), and 2700 to 3000 (2952 to 3280) meters (yd). Aspect classes were N, NE, E, SE, S, SW, W, and NW. We plotted a coarse-scale map of slope, aspect, and elevation for the study area showing these broad spatial patterns.

U.S. Geological Survey (GS) topographic maps, at 1:100,000, were indispensable to interpret land surface form, drainage patterns, slope, aspect, and elevation and were used as base maps for this project.

Conclusion

The type and distribution of substrate; habitat complexity operating at many spatial scales; the amount, timing, and quality of water; the type and amount of riparian vegetation; and interactions among biota are influenced by multiple landscape characteristics, sometimes acting synergistically to cause a stronger response or perhaps acting antagonistically to mitigate the influence. It is impossible to predict stream habitat at any given point based upon a landscape classification because: (1) landscape properties are not black and white and do not operate independently but interact either synergistically or antagonistically with other landscape properties; (2) the effects of upslope processes are not the same throughout a basin, but vary depending upon the size of the stream, valley morphology, and slope; and (3) the influence of different types and intensities of land uses needs to be considered.

Landscape-level ecoregions are a tool that may be useful in understanding and managing stream ecosystems. Years of process-level research will allow us to begin to understand the direction and intensity of these multiple interacting processes. We feel landscape-level ecoregions can help focus process-level research and that future process-level research can help refine these regions in a positive feedback loop. Because in the interim, which inevitably will be a substantial time frame, we are forced to make management decisions, we have proposed these landscape-level ecoregions as a level of stratification to help make local land management decisions. A landscape-level classification can help identify: (1) potential areas from which to pick reference sites, (2) areas that may be sensitive to land-use effects, (3) potential monitoring and research sites, (4) areas to extrapolate the results from finer scale process-level research, and (5) the potential capacity of a stream.

Before incorporating landscape-level ecoregions into future research or management strategies, the landscape-level ecoregions should be evaluated. We agree with Warren's (1979) assessment that "potential capacity is a very abstract theoretical concept amenable only to very indirect and partial evaluation." He also states that "although in no ordinary sense can a classification be shown to be true or false, validation of a sort is important." We have chosen to use the word *evaluate* instead of *validate* because evaluate expresses the element of judgment rather than proof.

By providing the logical underpinnings for the delineation of the map units, potential users will be able to assess the usefulness of this classification for their specific project objectives. This critical evaluation is the first step in evaluating a classification. The next step is a statistical analysis, as was done by Whittier and others (1988). They used multivariate analysis of biotic assemblages, physicochemical measures, species richness, diversity, and composition from small, minimally impacted streams to evaluate the robustness of Omernik's ecoregion classification in Oregon. Three approximately 100-meter-long (109-yd-long) reaches that encompassed complete sets of the characteristics stream habitat types for that site were sampled for six streams within each ecoregion. They found that as a whole streams within an ecoregion tend to be like other streams in that region and unlike streams in other regions. The Principal Components Analysis (PCA) ordination for physical habitat shows regional patterns, however, the distribution of the Blue Mountains and Columbia Basin[9] ecoregion's streams do not form a tight cluster pattern. Finer-scale classifications, i.e., subregions and landscape-level ecoregions may further explain some of the variability within ecoregions.

Ongoing research is focusing on evaluating the usefulness of landscape-level ecoregions for assessing the variability of stream habitat and fish distribution using survey data. Based upon this and future work, it may be advantageous to combine some regions if they are physically similar and respond to stresses similarly. Regions may also be combined to meet specific project goals. Survey data should be both spatially and temporally representative of potential stream capacity. The best indicator of a stream's potential capacity results from analyzing fish distribution and stream habitat survey data from streams in a relatively unimpacted condition. Data can be from either historic or present surveys, and we recognize that data of this nature is very limited, especially for low-elevation areas. Warren (1979) states "if a classification is to serve management purposes, systems within a class must respond similarly to similar environmental conditions including resource utilization and environmental management." Following the logic of Warren (1979), data from disturbed streams may help evaluate the landscape delineation because just as a stream's potential capacity may vary between regions, reaction to disturbance may also vary between regions. Because a stream's reaction to disturbance is frequently a simplification of the channel (Bisson and others 1992, Henjum and others 1994, Hicks and others 1991), evaluating significant differences in stream habitat characteristics between regions and understanding a stream's potential capacity is more difficult. However, a stream's response to disturbance also varies with timing and character of last disturbance as related to natural disturbance regime. In addition, using data from disturbed streams requires knowledge of land-use history. For example, the headwaters of the upper Grande Ronde River have historically been dredge mined (McIntosh and others 1994). Stream-habitat survey data from 1941 showed no large pools in this area. Recent resurveys—(1990), found several large pools in the same stretch of rivers. However, most of these pools were attributed to the artificial pool-forming structures that were added to enhance habitat.[10] Without knowledge of these events, erroneous conclusions could be drawn from analysis of this stream habitat data.

Future work should focus on identifying the potential of a system using reference sites, historical stream data, and expert knowledge and grappling with the issues of differences in the magnitude of upslope and upstream effects. We hope that more work will also be done on classifying watersheds from their mix of ecoregions, identifying appropriate questions for different scales in the hierarchy, and overlaying information on human disturbances to assess the capability of ecosystems in each ecoregion to deal with different types and intensities of stressors.

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Corporation. It has been subjected to the EPA's peer and administrative review and approved for publication.

Table 1 – Native vegetation defining Columbia Plateau subregions (fig. 3 by legend number)

Subregion	Genus species	Common name
Channeled Scablands (10a)	*Artemisia rigida*	Stiff sage
	Poa sandbergii	Sandberg's bluegrass
Loess Islands (10b)	*Artemisia tridentata*	Big sage
	Agropyron spicatum	Bluebunch wheatgrass
	Festuca idahoensis	Idaho fescue
	Artemisia tripartita	Threetip sage
Umatilla Plateau (10c)	*Agropyron spicatum*	Bluebunch wheatgrass
	Festuca idahoensis	Idaho fescue
	Rosa spp	Rose
	Crataegus spp.	Hawthorne
	Symphoricarpus albus	Common snowberry
Okanogan Drift Hills (10d)	*Artemisia tridentata*	Big sage
	Agropyron spicatum	Bluebunch wheatgrass
	Artemisia tripartita	Threetip sage
	Festuca idahoensis	Idaho fescue
	Purshia tridentata	Bitterbrush
	Pinus ponderosa	Ponderosa pine

Pleistocene Lake Basins (10e)	*Artemisia tridentata*	Big sage
	Agropyron spicatum	Bluebunch wheatgrass
Canyons and Dissected Uplands (10f)	*Rosa spp*	Rose
	Symphoricarpus albus	Common snowberry
Yakima Folds (10g)	*Artemisia tridentata*	Big sage
	Agropyron spicatum	Bluebunch wheatgrass
	Festuca idahoensis	Idaho fescue
	Hieracium spp.	Hawkweeds
	Purshia tridentata	Bitterbrush

Table 2—Native vegetation defining Blue Mountain subregions (fig. 3 by legend number)

Subregion	Genus species	Common name
--Subalpine areas (11m)	*Abies lasiocarpa*	Subalpine fir
	Pinus contorta	Lodgepole pine
	Larix occidentalis	Western larch
	Picea engelmanii	Engelmann spruce
	Pinus albicaulis	Whitebark pine
Subregions in the Cascade Rainshadow		
--John Day/Clarno Uplands (11a)	*Juniperus occidentalis*	Western juniper
	Aretemisia tridentata	Big sagebrush
	Purshia tridentata	Bitterbrush
	Agropyron spicatum	Bluebunch wheatgrass
	Festuca Idahoensis	Idaho fescue
	Poa sandbergii	Sandberg's bluegrass

--John Day/Clarno Highlands (11b)	*Pinus ponderosa*	Ponderosa pine
	Pinus contorta	Lodgepole pine
	Psuedotsuga menziesii	Douglas-fir
	Purshia tridentata	Bitterbrush
	Cecocarpus ledifolius	Mountain mahogany
	Agropyron spicatum	Bluebunch wheatgrass
	Calamagrostis rubescens	Pinegrass
	Carex geyeri	Elk sedge
Maritime-Influenced Zone (11c)		
--Mesic Forest Section (11l)	*Abies grandis*	Grand fir
	Psuedotsuga menziesii	Douglas-fir
	Pinus contorta	Lodgepole pine
	Picea engelmannii	Engelmann spruce
	Larix occidentalis	Western larch
	Abies lasiocarpa	Subalpine fir
	Linnaea borealis	Twinflower
	Spirea betulfolia	Birchleaf spirea
	Acer glabrum	Rocky Mountain maple
	Taxus brevifolia	Pacific yew
	Vaccinium membranaceum	Big huckleberry
	Vaccinium scoparium	Grouse huckleberry

--Subalpine areas (11m)	*Abies lasiocarpa*	Subalpine fir
	Pinus contorta	Lodgepole pine
	Larix occidentalis	Western larch
	Picea engelmanii	Engelmann spruce
	Pinus albicaulis	Whitebark pine
Melange Subregion (11d)	*Pinus ponderosa*	Ponderosa pine
	Juniperus occidentalis	Western juniper
	Psuedotsuga menziesii	Douglas-fir
	Cercocarpus ledifolius	Mountain mahogany
	Purschia tridentata	Bitterbrush
	Ribes cereum	Squaw current
	Symphoricarpos	Snowberry
	Calamagrostis rubescens	Pinegrass
	Carex geyeri	Elk sedge

--Mesic Forest Section (11l)	*Abies grandis*	Grand fir
	Psuedotsuga menziesii	Douglas-fir
	Pinus contorta	Lodgepole pine
	Picea engelmannii	Engelmann spruce
	Larix occidentalis	Western larch
	Abies lasiocarpa	Subalpine fir
	Linnaea borealis	Twinflower
	Spirea betulfolia	Birchleaf spirea
	Acer glabrum	Rocky Mountain maple
	Taxus brevifolia	Pacific yew
	Vaccinium membranaceum	Big huckleberry
	Vaccinium scoparium	Grouse huckleberry
--Subalpine areas (11m)	*Abies lasiocarpa*	Subalpine fir
	Pinus contorta	Lodgepole pine
	Picea engelmannii	Engelmann spruce
	Pinus albicaulis	Whitebark pine
	Artemisia tridentata	Alpine sagebrush
	Idaho fescue	Idaho fescue
	Festuca viridula	Green fescue
	Carex geyeri	Elk sedge
	Carex hoodii	Hood's sedge

Wallowas/Seven Devils Subregion (11e)	*Pinus ponderosa*	Ponderosa pine
	Psuedotsuga menziesii	Douglas-fir
	Physocarpus malvaceus	Mallow ninebark
	Symphoricarpos albus	Common snowberry
	Acer glabrum	Rocky Mountain maple
	Amelanchier alnifolia	Western serviceberry
	Purschia tridentata	Bitterbrush
	Artemisia tridentata vaseyana	Mountain big sagebrush
--Mesic Forest Section (11l)	*Abies grandis*	Grand fir
	Abies lasiocarpa	Subalpine fir
	Clintonia uniflora	Queen's cup beadlily
	Vaccinium scoparium	Big huckleberry
--Subalpine areas (11m)	*Abies lasiocarpa*	Subalpine fir
	Picea engelmanii	Engelmann spruce
	Tsuga mertensiana	Mountain hemlock
	Festuca viridula	Green fescue
	Carex hoodii	Hood's sedge
Canyons and dissected highlands (11f)	*Pinus ponderosa*	Ponderosa pine
	Psuedotsuga menziesii	Douglas-fir
	Larix occidentalis	Western larch
	Abies grandis	Grand fir

Snake and Salmon River Canyons (11g)	*Pinus ponderosa*	Ponderosa pine
	Purschia tridentata	Bitterbrush
	Rosa	Rose
	Symphoricarpos albus	Common snowberry
	Glossopetalon nevadense	Spiny greenbush
	Agropyron spicatum	Bluebunch wheatgrass
	Poa sandbergii	Sandberg's bluegrass
	Festuca idahoensis	Idaho fescue
Continental Zone Highlands (11h)	*Pinus ponderosa*	Ponderosa pine
	Psuedotsuga menziesii	Douglas-fir
	Artemisia tridentata	Big sagebrush
	Cecocarpus ledifolius	Mountain mahogany
	Purschia tridentata	Bitterbrush
	Ribes cereum	Squaw current
	Calamagrostis rubescens	Pinegrass
	Carex geyerii	Elk sedge

Continental Zone Foothills (11i)	*Juniperus occidentalis*	Western juniper
	Artemisia rigida	Rigid sagebrush
	Artemisia arbuscula	Low sagebrush
	Cercocarpus ledifolius	Mountain mahogany
	Purschia tridentata	Bitterbrush
	Artemisia tridentata	Mountain big sagebrush
		Idaho fescue
	Festuca idahoensis	Bluebunch wheatgrass
	Agropyron spicatum	
Batholith Contact Zone (11j)	*Pinus ponderosa*	Ponderosa pine
	Psuedotsuga menziesii	Douglas-fir
	Physocarpus malvaceus	Ninebark
	Calamagrostis rubescens	Pinegrass
--Mesic Forest Section (11l)	*Pinus ponderosa*	Ponderosa pine
	Larix occidentalis	Western larch
	Pinus contorta	Lodgepole pine
	Picea engelmannii	Engelmann spruce

Blue Mountain Basins (11k)	*Symphoricarpus albus*	Common snowberry
	Sarcobatus sp.	Greasewood
	Festuca idahoensis	Idaho fescue
	Poa sandbergii	Sandberg's bluegrass
	Deschampsia caespitosa	Tufted hairgrass
	Agrostis diegoensis	Redtop bentgrass
	Carex sp.	Sedges

Table 3—Factors that vary the risk of sedimentation limiting salmonid populations by habitat degradation[a]

Factor	Level of risk			
	Decreasing . . .	. . . .	. . . .	. . . . Increasing
Climate	Winter rain	Summer rain, Winter snow	Spring snowmelt	Spring-fed
Erosive processes	Surface erosion, channel erosion	Surface and mass erosion	Mass erosion	
Geology	Metavolcanics, volcanic	Sandstone, siltstones	Granitic	
Topography lands	Gentle terrain	Moderate terrain	Steep terrain	
Stream gradient	High (> 5%)	Moderate (1–5%)	Low (< 1%)	
Channel morphology				
	Narrow-deep	. . . .	. .	. . . . Shallow-wide
Riparian vegetation				
	Abundant	. . . .	. . . .	. . . . Scarce

[a]From Everest and others (1987).

Table 4—Relative importance of landscape factors controlling water quality elements in the Pacific Northwest Coastal Ecoregion[a]

Controlling factor	Water quality element				
	Nitrogen	Phosphorus	Turbidity	Temperature	Intragravel DO
Climatic and atmospheric inputs	H	L	M	H	L
Geology and soil	M	H	H	M	H
Stream order	M	M	M	H	M
Constrained or unconstrained	H	H	H	M	M
Vegetation	H	M	M	M	L

[a]From Naiman and others (1992); importance is coded as H-high, M-medium, and L-low.

Table 5—Source maps used to delineate landscape-level ecoregions

Landscape characteristic	Scale	Subject	Source	Date	GIS	Minimum mapping unit
Topography	1 250,000	Digital Elev Models (DEM)	GS 1987	1970-1981	Y	60 x 90 m (66 - 98 yd) grid
	1 100,000	Topographic Maps	USGS	1979-1982	N	
Soil	1 250,000	STATSGO (OR & WA)	SCS	1993	Y	625 ha 1544 ac
	1 63,360	National Forest Soil Resource Inventories	Carlson (Malheur)	1974	N	
			Paulson (Ochoco)			
			Ehmer (Umatilla)	1977	N	20 ha 50 ac
			Wallowa-Whitman NF			
				N y	N	
				1993	Y	
	1 20,000-1 31,680	County Soil Surveys	SCS*	1962-1991	N	2 ha 5 ac
Climate	1 500,000	Normal Annual Precipitation	Taylor (OSU)	1994	Y	8 km (4.97 mi) grid
	1·2,000,000	Precipitation Map (WA)	Miller (NOAA) Digital WADNR	1973	Y	
	1 250,000	Rain-on-snow Zones (WA)	Brunengo (WADNR)	1991	Y	

Geology	1.500,000	Geology (OR)	Walker and MacLeod (USGS)	1991	Y
	1 250,000	Geology (SEWA)	Johnson and Derkey (USGS)	1993	Y
	1:24,000	Granite Quad (OR)	Brooks and others (USGS)	1982	N
	1 250,000	Canyon City Quad (OR)	Brown and Thayer (USGS)	1966	N
	1·62,500	Desolation Butte Quad (OR)	Evans (USGS)	1989	N
	1 24,000	Limber Jim Quad (OR)	Ferns & Taubenack (USGS)	1994	N
	1·100,000	Connell Quad (WA)	Gulick (WADNR)	1994	N
	1 100,000	Pullman Quad (WA)	Gulick (WADNR)	1994	N
	1 125,000	John Day Formation (OR)	Robinson	1975	N
	1 100,000	Clarkston Quad (WA)	Schuster (WADNR)	1993	N
	1 100,000	Walla Walla Quad (WA)	Schuster (WADNR)	1994	N
	1.250,000	Pendleton Quad (OR & WA)	Walker (USGS)	1973	N
	1 250,000	Grangeville Quad (OR & WA)	Walker (USGS)	1979	N
	1.250,000	Columbia River Basalt Group (WA & ID)	GS	1980	N
	1.100,000	Lignite and coal resources (NE OR)	Ferns (DOGAMI)	1985	N
	1·250,000	Umatilla Indian Res (OR)	Gonthier and Bolke (USGS)	1993	N

	1:62,500	Upper Grande Ronde River basin (OR)	Hampton and Brown (USGS)	1964	N	
	1:127,000 (approx.)	Umatilla River basin (OR)	Hogenson (USGS)	1964	N	
	1:95,000 (approx.)	Walla Walla River basin (OR & WA)	Newcomb (USGS)	1965	N	
Vegetation	1:63,360	Forest type class (OR & WA)	USFS	1935-1960	Y	
	1:253,000 (approx.)	Forest type map (OR)	USFS	1936	N	
	1:253,000 (approx.)	Forest type map (WA)	USFS	1936	N	
	1:250,000	Actual vegetation (OR)	Kagan and Caicco (U of ID)	1992	Y	133 ha 328 ac

[a]Dyksterhuis 1981, Dyksterhuis and High 1985, Gentry 1991, Harrison and others 1962, 1973, Hosler 1983; Johnson and Makinson 1988, NRCS 1995, unavailable—Wheeler County, Oregon

Table 6—Principal soil series names for map units defined primarily by soil characteristics. Soil series names from STATSGO and county soil surveys

Map unit	Description	Dominant subregion(s)	Soil series names
gela/v	Grassland eolian lacustrine valley	11k Blue Mountain Basins	Imbler Alicel Palouse
gla/v	Grassland lacustrine deposits	11k	Hot Lake Conley
gaf	Grassland alluvial fans	11k	Catherine LaGrande
gloa	Grassland loess and ash on uplands	11k	Watama Ramo McMurdie

grca	Grassland loess and residuum over cemented alluvium	11k	Albee
ggl/v	Grassland gravelly lacustrine deposits	10f Canyons and Dissected Uplands	Lostine Ladd Langrell
gcl	Grassland cobbly loam	10f	Hurwal Snell Ateron
glowx/h	Grassland warm, xeric loess w/ salts on plateaus and hills	10f	Nims Weissenfels Olical Stember Neissenberg Peola

glox/h	Grassland xeric loess on plateaus and hills	10f	Neconda Ferdinand Powwahkee
glocx/p	Grassland cool, xeric loess on plateaus	10f	Sweitberg Snell
glod/h	Grassland deep loess on hills	10i Deep Loess Foothills	Athena Palouse Peola
gxca	Grassland xeric loess over cemented alluvium	10c Umatilla Plateau 11k Blue Mountain Basins	Bocker Bridgecreek Potomus
glomd/h	Grassland moderately- deep loess on hills	10c	Gwin Waha Rockly Gurdane

glos/h	Grassland shallow loess on hills	10c	Gwin Gurdane Rockly
glodx/h	Grassland deep, xeric loess on hills	10c 10b Scabland Loess Islands	Walla Walla
gbs/h	Grassland biscuit scabland on hills	10c	Morrow Bakeoven Condon
gloal	Grassland deep loess and old alluvium	10c	Pilot Rock McKay
ges	Grassland eolian sands	10e Pleistocene Lake Basins	Quincy Sagehill Hezel

ggfg	Grassland glaciofluviate gravel deposits	10e	Quincy Hezel
ggfs	Grassland glaciofluviate sand and silt deposits	10e	Ellisforde Sagemoor
ggo/t	Grassland aridic glacial outwash on terraces	10e	Farrell Roloff
gaca	Grassland aridic loess over cemented alluvium	10e	Shano Burke
gloda/h	Grassland deep, aridic loess on hills	10b Scabland Loess Islands	Ritzville Ellisforde

Table 7—Properties for ash-, sandstone-, and basalt-derived soil[a]

	Properties				
Soil fragments	Bulk density	Porosity	Clay	Coarse fragment	Available water
	Mg/mm^3	*Percent volume*	*Percent weight*	*Percent volume*	*Percent volume*
Ash	0.6-0.7	73-77	3-10	0-4	26-30
Basalt	0.9	65	20	30	13
Sandstone	1.6	40	10	0	14

[a]Adapted from Harvey and others (1994).

Table 8—Characteristics of soils by texture[a]

Soil texture	Porosity	Permeability
	Percent	*M/d*
Clay	45–60	0.00001–0.001
Silt	20–50	0.01–10
Sand	30–40	10–100,000
Gravel	25–40	1,000–10,000,000

[a]From Gregory and Walling (1973).

Table 9—Stocking per acre in trees at 6 inches average diameter at breast height (DBH)[a]

Tree	Number stocked
Ponderosa pine/grassland	63–238
Ponderosa pine	214–415
True fir	285–620
Subalpine fir	245–480

[a]Ten rings per inch of growth. From Hall (1973a).

Table 10—Characteristics of the forest zones

Forest zone Elevation range Annual precipitation range	Tree species	Shrub species	Grass and forb species
Juniper 760-1400 m (2483-4593 ft) 20-30 cm (8-12 in)	Western Juniper (*Juniperus occidentalis*)	Bitterbrush (*Purshia tridentata*) Big sagebrush (*Artemisia tridentata*) Mountain-mahogany (*Cercocarpus ledifolius*)	Idaho fescue (*Festuca idahoensis*) Bluebunch wheatgrass (*Agropyron spicatum*) Elk sedge (*Carex geyeri*)
Ponderosa pine 900-1500 m (2953-4921 ft) 35-76 cm (14-30 in)	Ponderosa pine (*Pinus ponderosa*) Grand fir (*Abies grandis*) White fir (*Abies concolor*) Western larch (*Larix occidentalis*) Douglas-fir (*Psuedotsuga menziesii*) Lodgepole pine (*Pinus contorta*) Western white pine (*Pinus monticola*)	Mountain-mahogany (*Cercocarpus ledifolius*) Common snowberry (*Symphoricarpos albus*) Mountain snowberry (*Symphoricarpos oreophilus*) Bitterbrush (*Purshia tridentata)* Mountain big sagebrush (*Artemisia tridentata vaseyana*)	Elk sedge (*Carex geyeri*) Idaho fescue (*Festuca Idahoensis*) Pinegrass (*Calamagrostis rubescens*) Wheeler's bluegrass (*Poa nervosa*) Bluebunch wheatgrass (*Agropyron spicatum*)

Douglas-fir	Douglas-fir (*Psuedotsuga menziesii*) Ponderosa pine (*Pinus ponderosa*) Western larch (*Larix occidentalis*) Lodgepole pine (*Pinus contorta*)	Rocky Mountain maple (*Acer glabrum*) Mallow ninebark (*Physocarpus malvaceus*) Big huckleberry (*Vaccinium membranaceum*) Mountain snowberry (*Symphoricarpos oreophilus*) Common snowberry (*Symphoricarpos albus*) Birchleaf spiraea (*Spiraea betulfolia*) Oceanspray (*Holodiscus discolor*)	Western fescue (*Festuca occidentalis*) Pinegrass (*Calamagrostis rubescens*) Elk sedge (*Carex geyeri*)

True fir 1500-2000 m (4921-6562 ft) 63-115 cm (25-45 in)	Grand fir (*Abies grandis*) White fir (*Abies concolor*) Ponderosa pine (*Pinus ponderosa*) Lodgepole pine (*Pinus contorta*) Larch (*Larix occidentalis*) Douglas-fir (*Pseudotsuga menziesii*) Western white pine (*Pinus monticola*)	Pacific yew (*Taxus brevifolia*) Thimbleberry (*Rubus parviflorus*) Twinflower (*Linnaea borealis*) Big huckleberry (*Vaccinium membranaceum*) Grouse huckleberry (*Vaccinium scoparium*)	Oakfern (*Gymnocarpium dryopteris*) Coolwort foamflower (*Tiarella trifoliata unifoliata*) Hooker's fairy bells (*Disporum hookeri*) Sword fern (*Polystichum munitum*) Queen's cup beadlily (*Clintonia uniflora*) Pinegrass (*Calamagrostis rubescens*) Columbia brome (*Bromus vulgaris*) Lupine (*Lupinus*) Elk sedge (*Carex geyeri*) Ginger (*Asarum caudatum*)

Subalpine fir 1300-1700 m (4265-5577 ft)	Subalpine fir (*Abies lasiocarpa*) Engelmann spruce (*Picea engelmannii*) Lodgepole pine (*Pinus contorta*) Western larch (*Larix occidentalis*) Whitebark pine (*Pinus albicaulis*) Douglas-fir (*Pseudotsuga menziesii*)	Big huckleberry (*Vaccinium membranaceum*) Fool's huckleberry (*Menziesia ferruginea*) Grouse huckleberry (*Vaccinium scoparium*)	Heartleaf arnica (*Arnica cordifolia*) Queen's cup beadlily (*Clintonia uniflora*) Sidebells pyrola (*Pyrola secunda*) Elk sedge (*Carex geyeri*)

Table 11—Species composition of the nonforested zones

Zone	Dominant shrub species	Dominant grass species
Aridic grassland	Bitterbrush (*Purshia tridentata*)	Needle and thread (*Stipa comata*)
	Basin big sagebrush (*Artemisia tridentata spp tridentata*)	Sandberg's bluegrass (*Poa sandbergii*)
		Indian ricegrass (*Oryzopsis hymenoides*)
		Bluebunch wheatgrass (*Agropyron spicatum*)
Sagebrush	Mountain big sagebrush (*Artemisia tridentata spp vaseyana*)	Elk sedge (*Carex Geyeri*)
		Idaho fescue (*Festuca idahoensis*)
	Low sagebrush (*Artemisia arbuscula*)	Sandberg's bluegrass (*Poa sandbergii*)
	Stiff sagebrush (*Artemisia rigida*)	Bluebunch wheatgrass (*Agropyron spicatum*)
Xeric grassland		Bluebunch wheatgrass (*Agropyron spicatum*)
		Sandberg's bluegrass (*Poa sandbergii*)
Mesic grassland		Idaho fescue (*Festuca idahoensis*)
		Prairie junegrass (*Koelaria cristata*)
		Bluebunch wheatgrass (*Agropyron spicatum*)
		Hood's sedge (*Carex hoodii*)

Shrublands	Ninebark (*Physocarpus malvaceus*) Common snowberry (*Symphoricarpos albus*) Oceanspray (*Holodiscus discolor*) Cherries (*Prunus*) Mountain-mahogany (*Cercocarpus ledifolius*)	Bluebunch wheatgrass (*Agropyron spicatum*) Idaho fescue (*Festuca idahoensis*) Wheeler's bluegrass (*Poa nervosa*)
Alpine	Alpine sagebrush (*Artemisia tridentata spp. vaseyana*)	Green fescue (*Festuca viridula*) Idaho fescue (*Festuca idahoensis*) Elk sedge (*Carex geyeri*)

FOOTNOTES

[1]Personal communication. 1995. J. Omernik, U.S. Environmental Protection Agency, National Health and Environmental Effects Laboratory, Western Ecology Division.

[2]Personal communication. 1995. E. Bishop, Oregon Watershed Health Program.

[3]Term range of natural variability coined by Rhodes and McCullough (1994).

[4]Principles used in defining the landscape-level ecoregions for anadromous fish and their habitat may make them applicable to other aquatic resource issues as well as some terrestrial resource issues. An assessment of the usefulness of the classification for other resources can be made by evaluating the map and reading the rationale section. Classes can be combined to meet the needs of other resource projects.

[5]Personal communication. 1995. J.J. Rhodes, Columbia River Inter-Tribal Fish Commission.

[6]SCS became the U.S. Department of Agriculture's National Resources Conservation Service (NRCS) in late 1994.

[7]Personal communication. 1994. M.L. Ferns, Wallowa-Whitman National Forest.

[8]Personal communication. 1994. E. Bishop, Oregon Watershed Health Program.

[9]Now referred to as the Columbia Plateau Ecoregion.

[10]Personal communication. 1995. Bruce Mcintosh, Forest Science Department, Oregon State University.

FIGURE CAPTIONS

Figure 1—Example of the interplay between ecoregions and watersheds.

Figure 2—Photos representing the diversity among subregions and landscape-level ecoregions for the Columbia Plateau and Blue Mountain Ecoregions.

Figure 3—Level IV ecoregions of the Columbia Plateau and Blue Mountain Ecoregions of Washington, Oregon, and Idaho.

Figure 4—A Boundary transition-width map included with the ecoregion/subregion map for the Columbia Plateau.

Figure 5—Study area watersheds.

Figure 6—Landscape-level ecoregions.

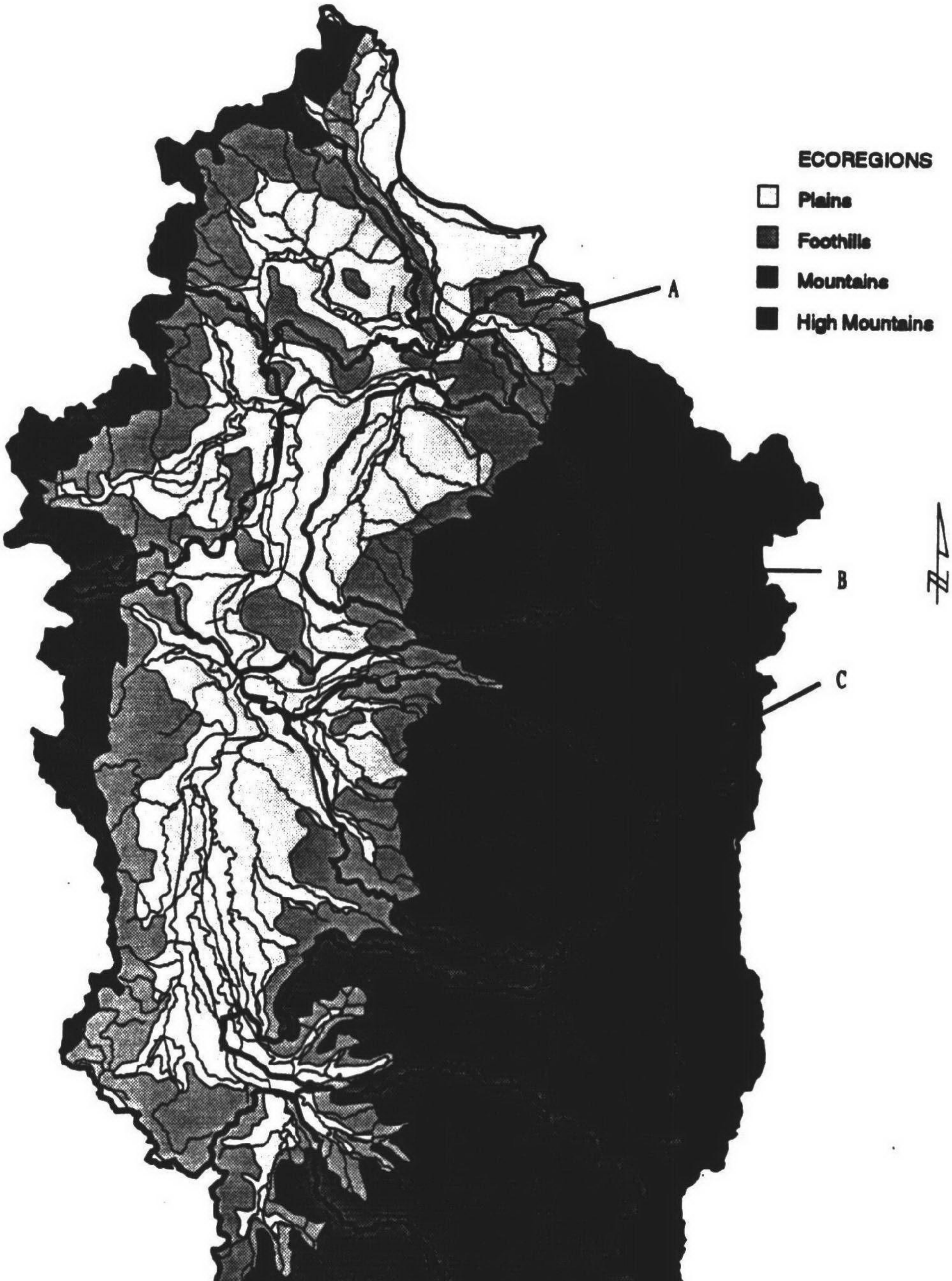
ECOREGIONS
Plains
Foothills
Mountains
High Mountains
A
B
C

Figure 1

Figure 2 - Photos

Figure 6 - Landscape-level ecoregions

MAP AND PHOTOS NOT AVAILABLE AT PRESENT.

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when published

COLUMBIA PLATEAU ECOREGION/SUBREGION BOUNDARY TRANSITION WIDTHS

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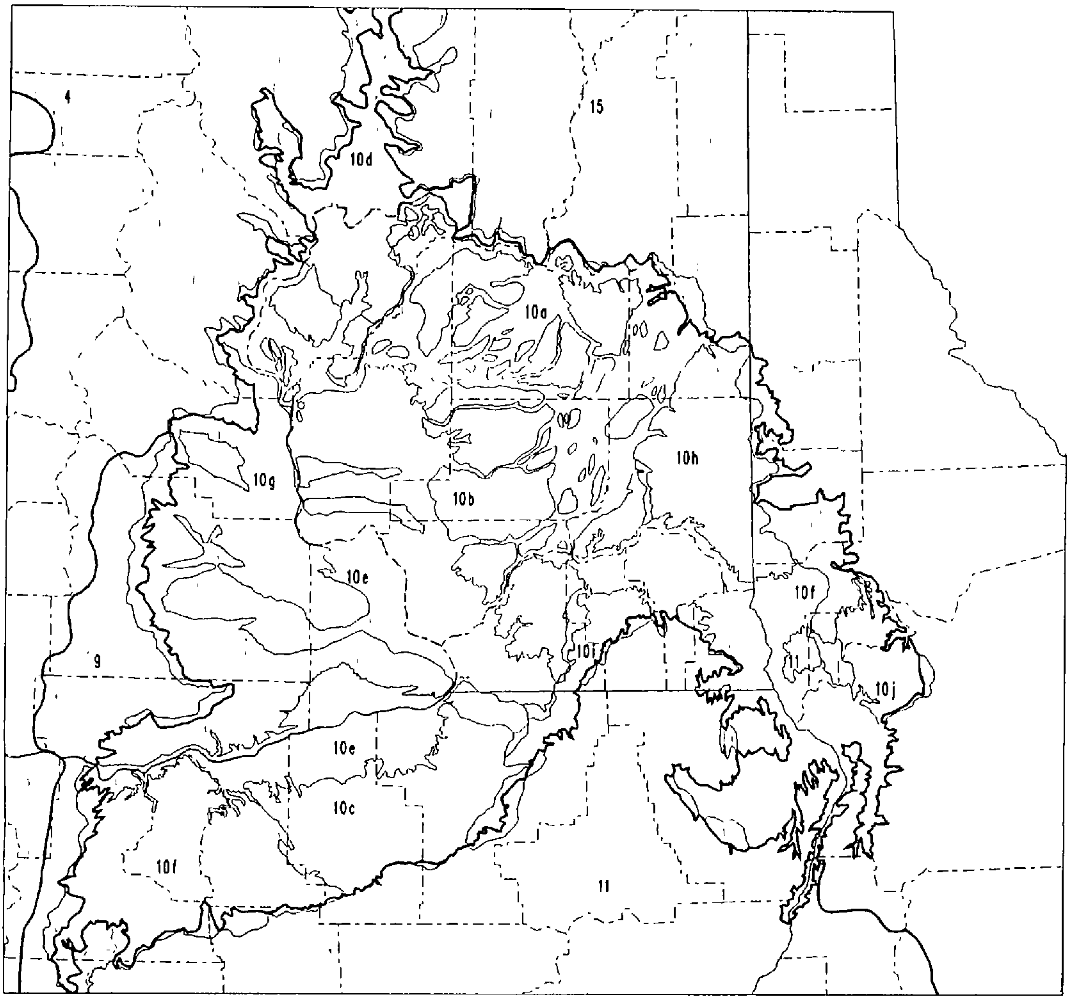


COLUMBIA PLATEAU (10)

Channeled Scablands (10a)

Scabland loess islands (10b)

Umatilla plateau (10c)

Okanogan drift hills (10d)

Pleistocene lake basin (10e)

Canyons and dissected uplands (10f)

Yakima folds (10g)

Palouse hills (10h)

Deep loess foothills (10i)

Nez Perce prairie (10j)

CASCADES (4)

EASTERN CASCADES SLOPES AND FOOTHILLS (9)

BLUE MOUNTAINS (11)

NORTHERN ROCKIES (15)

—— ecoregion boundary

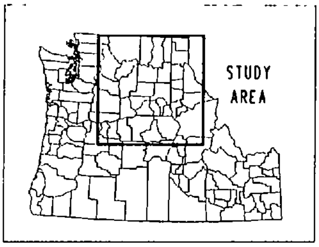
—— subregion boundary

fuzzy boundary

18 0 mi 18 36

36 0 km 36 72

Albers equal area projection



This map illustrates the relative widths of ecoregion and subregion boundaries. Regional boundaries are usually portrayed by single narrow lines on maps, but they represent transition zones of varying widths on the ground where characteristics of one area blend with those of another. The map shows how broad or narrow the transition areas appear to be as indicated by component maps and other sources of information. In some areas the change is distinct and abrupt such as where the Channeled Scablands(10a) meet the Loess Islands(10b). In other areas the transition is broad and the boundary is more difficult to determine. The fuzzy boundaries define areas of uncertainty or areas where there is a heterogeneous mosaic of characteristics from each of the adjacent subregions. It should be remembered that boundaries on a map are artifacts, abstractions and approximations. Because it is necessary and desirable to draw boundaries, our intent here is to provide the map user with more information about the process, nature, and meaning of the ecoregion delineations.

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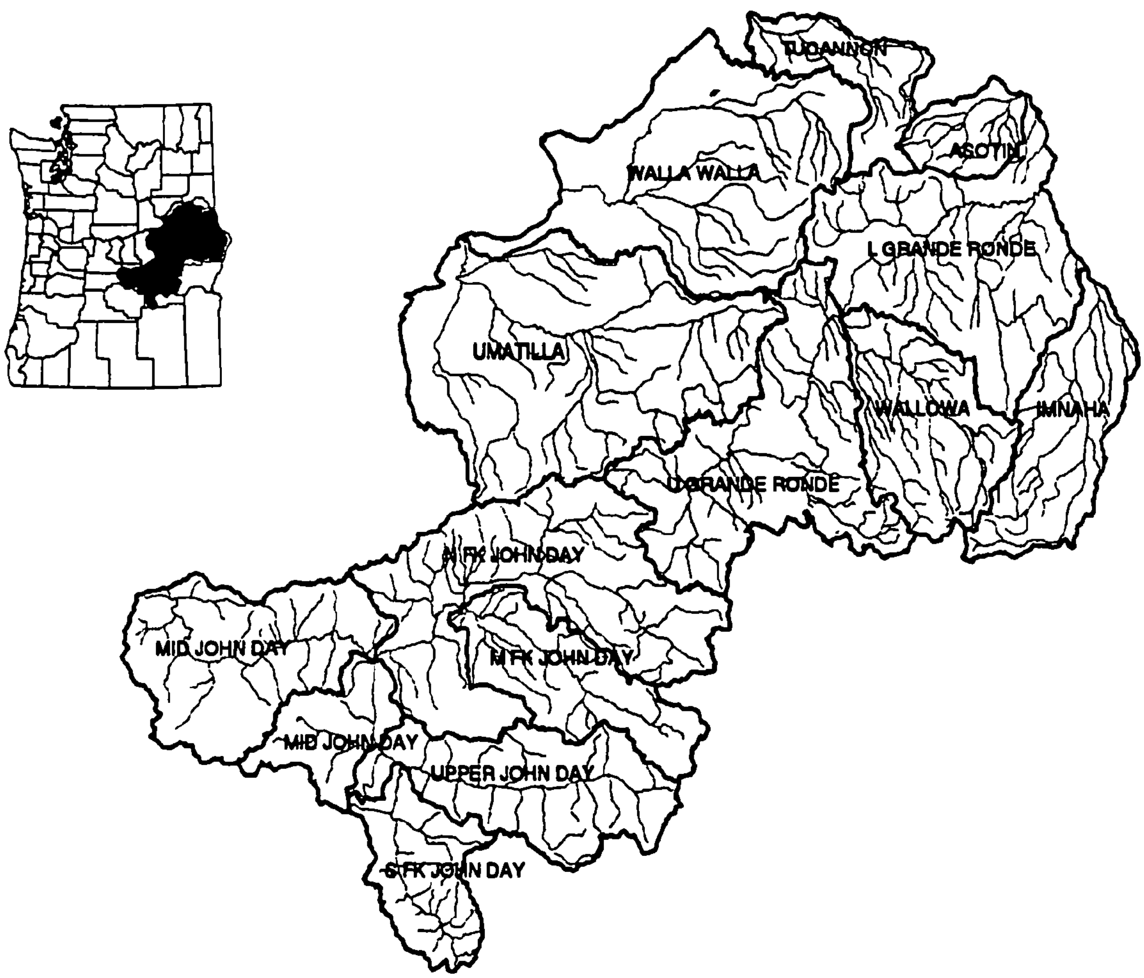
Seven Contiguous Watersheds in

N.E. Oregon and S.E. Washington



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