Biophysical Spectral Regionalization of the Pacific Northwest using Advanced Very High Resolution Radiometer Imagery

by

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Biophysical Spectral Regionalization of the Pacific Northwest using Advanced Very High Resolution Radiometer Imagery

ABSTRACT: Satellite imagery has become an efficient and time effective tool that may aid in the development of regional terrestrial and aquatic resource management schemes. A methodology utilizing National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) imagery, 1.1 kilometer spatial resolution at nadir, was developed for delineating homogeneous biophysical spectral regions across the Pacific Northwest (PNW). Biophysical spectral regionalization may provide state level resource managers and regional researchers with an organized and expeditious procedure for delineating area boundaries for a variety of natural resource management schemes.

INTRODUCTION

In recent years, conflicts over the use of aquatic and terrestrial resources have increased the need for a managerial framework that would recognize management units as a system of interacting and interdependent entities. Due to a renewed and heightened sense of national environmental awareness, it has become necessary for resource managers to spatially research, assess, monitor, and manage resources for the development and implementation of ecologically sound management schemes (Thiele et al., 1992, p.1). The need for a system-oriented management framework has prompted several agencies, such as the United States Environmental Protection Agency (EPA), the United States Forest Service (USFS), and Environment Canada to develop and outline such a framework suitable for state level management (Thiele, et al., 1992; Clarke, et al., 1991; Gallant, et al., 1989; Omernik and Gallant, 1990; Omernik, 1987; Omernik and Gallant, 1986; Wiken, 1986; Bailey, 1983).

Current trends in ecosystem management have increased the need for rapid resource assessment and inventory across regional boundaries. Many states, such as Ohio, Arkansas, and Minnesota, have already adopted the ecological region concept as the basis for their natural resource management units (Thiele, et al., 1992, p. 1). Other areas may be encouraged to utilize alternative regionalization schemes for management/study area boundaries if more time efficient methods of boundary delineation were adopted.

Contemporary developments in remote sensing have prompted researchers to use satellite imagery to investigate ecological aspects of the environment. Of these remote platforms, NOAA's AVHRR sensor is rapidly becoming an integral component of many regional and national research schemes (Cicone and Metzler, 1984; Cihlar et al., 1991; Goward et al., 1991; Paltridge and Barber, 1988; Townshend et al., 1991; Tucker et al., 1985).

The NOAA-11 AVHRR sensor is equipped with 5 spectral channels calibrated to receive and record reflectance values from various ecological and environmental features across the earth's surface (Table 1). The ability to collect ecological data and evaluate the imagery over regional scales would potentially make AVHRR imagery an important component in management regionalization schemes. AVHRR imagery provides a set of environmentally oriented spectral data that may be digitally processed to efficiently delineate homogenous regions.

Table 1: NOAA-11 AVHRR Sensor Characteristics*

Band	Spectral Channels (μm)	Sensitive Component
1	0.58 - 0.68	Vegetation
2	0.72 - 1.10	Water, Vegetation, Soil
3	3.55 - 3.93	Snow, Ice, Fires
4	10.5 - 11.50	Vegetation Stress, Geothermal
5	11.5 - 12.50	Vegetation Stress, Geothermal

*adapted from Lillesand and Kiefer, 1987, p. 592; ERDAS, 1990b., p. 29

Rapid resource assessment and area delineation using remote imagery may be accomplished through the process of biophysical spectral regionalization. Biophysical spectral regionalization is a recent term referring to the process of delineating homogeneous areas of biological and physical significance across the landscape according to their remotely sensed spectral reflectance values.

The objective of this research project was to develop a methodology, using AVHRR imagery, for the delineation of relatively homogeneous biophysical spectral regions across the Pacific Northwest.

STUDY AREA

The Pacific Northwest region (Figure 1), encompassing the states of Washington, Oregon, and Idaho, was the area examined for biophysical spectral regionalization. Physical characteristics of this study area are listed in Table 2.

Table 2: Physical Characteristics of the Pacific Northwest*

WASHINGTON	Kilometers	Miles
Land Area	172,350 km^2	66,570 mi^2
Water Area	4,199 km^2	1,622 mi^2
Coastline	253 km	157 mi
OREGON		
Land Area	249,020 km^2	96,184 mi^2
Water Area	2,063 km^2	797 mi^2
Coastline	476 km	296 mi
IDAHO		
Land Area	214,051 km^2	82,677 mi^2
Water Area	2,278 km^2	880 mi^2

*adapted from Kimerling and Jackson, 1985, p. 2.

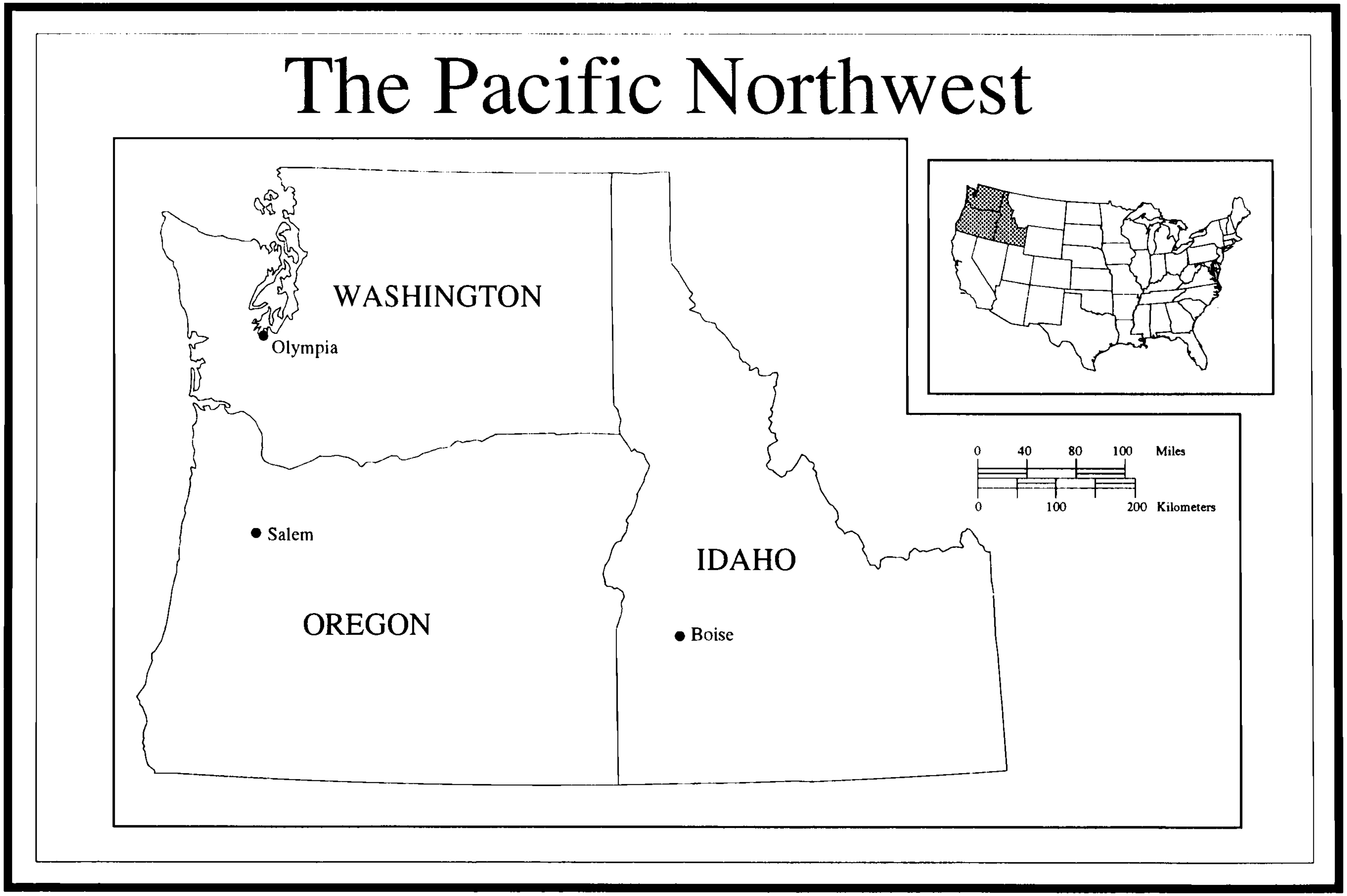
BACKGROUND

AVHRR Imagery

NOAA meteorological satellites were originally developed and designed to assist in weather prediction and the monitoring of atmospheric conditions. The AVHRR sensor has a swath width of 2400 kilometers (km); each pixel is either 1.1 or 4 km at nadir and becomes increasingly larger and distorted in area toward the outer extent of the swath (Lillesand and Kiefer, 1987, p. 592).

AVHRR imagery, with its relatively coarse resolution, is subject to a number of potential problems that should be considered prior to image processing and analysis. Sensor and ancillary complications that may effect a particular AVHRR image include: "sensor calibration, incidence solar irradiance, nominal atmospheric

Figure 1: Study Area



attenuation, variable spatial resolution and anisotropy with off-nadir views, and cloud occurrence (Goward et al., 1991, p. 274)."

The AVHRR image used in the biophysical spectral regionalization process was NOAA-11 High Resolution Picture Transmission (HRPT) data taken July 19, 1988, from the NOAA-9 polar orbiting satellite; orbit 18558.

Ecoregion Delineation

In order to explain the difference in the methodology for biophysical spectral regionalization, it is necessary to examine the most current concept for system oriented regionalization; the ecoregion. Although initially developed for water quality assessment and management, ecoregions are currently being used as study area boundaries for a variety of system oriented management schemes. Gallant et al. (1989, p. viii) define an ecoregion as "an area of relative homogeneity in ecological systems."

Wiken (1986) summarized ecological regionalization as:

> ... a process of delineating and classifying ecologically distinctive areas of the earth's surface. Each area can be viewed as a discrete system which has resulted from the mesh and interplay of the geologic, landform, soil, vegetative, climatic, wildlife, water and human factors which may be present. The dominance of any one or a number of these factors varies with the given ecological land unit. This holistic approach to land classification can be applied incrementally on a scale-related basis from very site-specific ecosystems to very broad ecosystems.

Varying philosophies and methodologies for delineating ecoregions are well documented (Thiele, et al., 1992; Clarke, et al., 1991; Gallant, et al., 1989; Omernik and Gallant, 1990; Omernik, 1987; Omernik and Gallant, 1986; Bailey, 1983). In general, multiple layers consisting of environmental characteristics such as geology, topography, climate, vegetation, land use, and soils are examined and manually transferred onto acetate overlays. Once the boundaries from each layer are compiled, they are examined and assigned values of the relative transition width of the region and its importance as an overall environmental component. Expert judgment is then applied across regional boundaries to determine which boundaries take precedence in terms of regional significance (Clarke, et al., 1991, p. 848). This same manual method of delineating ecoregions is also applied to subregional development.

Recently, the EPA Environmental Research Laboratory in Corvallis, Oregon, has also incorporated printouts of AVHRR normalized difference vegetation index (NDVI) composite images as another data layer in the ecoregional delineation scheme (Griffith, 1993, personal communication).

Bailey (1983) has approached the delineation of ecological regions in a more systematic and hierarchical fashion. Bailey's method of ecoregionalization is based upon a four tier hierarchical system that ranges from a regional broad climatic grouping to specific climax plant associations: Domain, Division, Province, and Section. According to Bailey (1983, p. 368) "vegetation serves as an indicator of climate," and therefore, "its geographical distribution serves as a primary recognition criterion for regional boundaries." "The map of the ecoregions of the United States depicts ecosystems of regional extent according to the Crowley classification (Crowley, 1967), with climate and vegetation as indicators of the extent of each unit.

More technological methods of ecoregionalization are slowly being developed, such as with Bernert, et al., (in press) who discuss a design to digitally delineate subecoregions of the Western Cornbelt Plains ecoregion.

These varying methods of ecoregionalization have provided the foundation for and will assist in the comprehension of the biophysical spectral regionalization process.

METHODS

All digital image processing, analysis, and map production took place at the Oregon State University Department of Forestry's Environmental Remote Sensing Applications Laboratory (ERSAL) and the Kerr Instructional Computer Lab. A synopsis of the computer hardware and software used throughout the project is given in Table 3.

Table 3: Project Equipment

Equipment	Purpose
Hardware	
IBM 486 Compatible Computer; 33 Mhz, 600 Mbyte hard drive	Digital image processing and data analysis
9-track cct reader	To transfer the original AVHRR imagery from the tape to the hard drive.
Calcomp 9100 Digitizer	To convert analog boundaries into digital form
Textronix 4696 ink jet printer	Final map production
HP laser jet printers	Final map production
Software	
ERDAS (1990a.) version 7.4	Image processing
AutoCAD (1992) version 12	Line map production
AutoScript (1992) version 5	Postscript map output
MicroCAM (1992)version 3.1	Digital map boundary production

The AVHRR image used in this study was initially transferred from a 1600 bpi 9-track computer compatible tape (cct) to an IBM compatible 486 computer. The 5 band, 36 megabyte image transferred from the cct contained 1800 rows and 2048 columns. The image was immediately viewed to check for undesirable features, such as bad scan lines or cloud cover. Most digital image processing systems have routines that allow bad scan lines to be removed by averaging the rows above and/or below the bad line. A total of 5 bad scan lines were eliminated from the original scene. The image, taken July 19, 1988, was virtually cloud free across the PNW so no cloud masking procedures were conducted. Only a few smoke plumes in the

Washington and Oregon Coast Range and a few high clouds located in the Rocky Mountains were visible in the image.

The raw AVHRR image encompassed an area from approximately 37 degrees to 55 degrees North latitude and 110 to 130 degrees West longitude. To reduce the file size and increase processing speed, a subset of the image was extracted containing the states of Washington, Oregon, and Idaho. Now that an image encompassing the PNW was available, it was necessary to rectify the image to a map projection coordinate system and to eliminate any geometric distortions across the scene.

Georeferencing

Georeferencing is "the process of assigning map coordinates to image data, and resampling the pixels of the image to conform to the map projection grid (ERDAS, 1990b., p. 383)." The first step in the georeferencing process was to locate a series of ground control points (GCP), points (pixels) where both the image file coordinates and geographic coordinates are known. Two methods of acquiring GCPs were used throughout the georeferencing process. One method utilized multiple listings from the Geographical Names Information System (GNIS) prepared by the United States Geological Survey (USGS) Branch of Geographic Names. (USGS, 1981a.; USGS, 1981b.; USGS, 1983). The GNIS is an alphabetical listing containing feature class names and geographic coordinates in degrees, minutes, and seconds for all of the features that appear on USGS topographic maps. The geographic coordinates found within the GNIS were used in conjunction with 1:500,000 USGS base maps of Washington, Oregon, and Idaho (USGS, 1968b.; USGS, 1982a.; USGS, 1982b.). Typically, AVHRR images are registered to permanent water bodies using band 2 (near-infrared) (Peters et al., 1992, p. 571; Kelly and Hood, 1991, p. 237). This method of using the GNIS in conjunction with the 1:500,000 maps allowed for points not entirely distinguishable on the image to be used as GCP sites. For example, a small city or locale is located on one of the 1:500,000 USGS base maps. The geographic listing and coordinate of that point may then be found within the GNIS. Once the location and geographic coordinate are identified, the file coordinates of the point must be located on the AVHRR image. This was accomplished by comparing the subject with nearby geographic phenomena, such as water bodies, river networks, islands, or mountain summits.

Another method of locating GCPs was to digitize points from a base map that was already referenced to a geographic coordinate system (USGS, 1962; USGS, 1966; USGS, 1968a.). Once the map was registered on the digitizing tablet, the digitizer may be used to obtain points anywhere on the image. This was particularly useful for areas that are not typically identified on USGS maps, such as the confluence of two rivers, or at the base of prominent landform features.

The next step in the georeferencing process was to create a transformation matrix so the AVHRR image could be rectified into a planimetrically correct orientation. Within the matrix, root mean square (RMS) errors were calculated for the transformation. A RMS error is "the distance between the input (source) location of a GCP, and the retransformed location for the same GCP (ERDAS, 1990b., p. 392)." The equation for calculating RMS error is as follows:

$$\sqrt{(x_r - x_i)^2 + (y_r - y_i)^2}$$

where:
x_i and y_i are the input source coordinates;
x_r and y_r are the retransformed coordinates.

"By computing RMS error for all GCPs, it is possible (1) to see which GCPs exhibit the greatest error, and (2) to sum all the RMS error (Jensen, 1986, p. 105)." The accuracy of GCP location will determine the quality of the image rectification.

Rectification

Rectifying an image is "the process of making image data conform to a map projection system (ERDAS, 1990b., p. 391)." The first rectification was designed to simplify the process of locating GCPs by making the scene more planimetrically correct. The initial rectification, based on 12 GCPs, was conducted using a first order (linear) transformation to minimize error between points. The total rms error was 0.80 pixels with an "x" error of 0.44 and a "y" error of 0.67.

Peters et al (1992, p.571) stressed the importance of the "areal ground coverage of each pixel" across an image. A cell size of .0127 degrees of latitude by .00901 degrees of longitude was used for constant scale at 44 degrees North latitude (Isaacson, 1993, personal communication). Nearest neighbor interpolation was used as the resampling method during the linear rectification.

A total of 100 GCPs evenly distributed throughout the PNW were used for the final rectification (Figure 2). In general, GCPs were more evenly distributed across the states of Washington and Oregon than in Idaho. The lack of spectrally identifiable features in the Idaho landscape made it difficult to positively locate suitable GCPs.

Initially, a second order polynomial equation was to be used in the construction of the transformation matrix for the second rectification, however, it was only possible to obtain a rms error of 3.5 pixels while maintaining a suitable number of GCPs. A third order transformation was then used for the final rectification. Higher order transformations typically experience an increase in error between GCPs. The third order transformation matrix produced a total rms error of 1.45 pixels with a "x" error of 1.13 and a "y" error of 0.91 pixels.

In order to evaluate the between-point error on the rectified image, several features such as rivers, lakes, and other distinguishable landforms were digitized throughout the PNW. The digitized features were then overlaid upon the rectified

Figure 2: GCP Locations

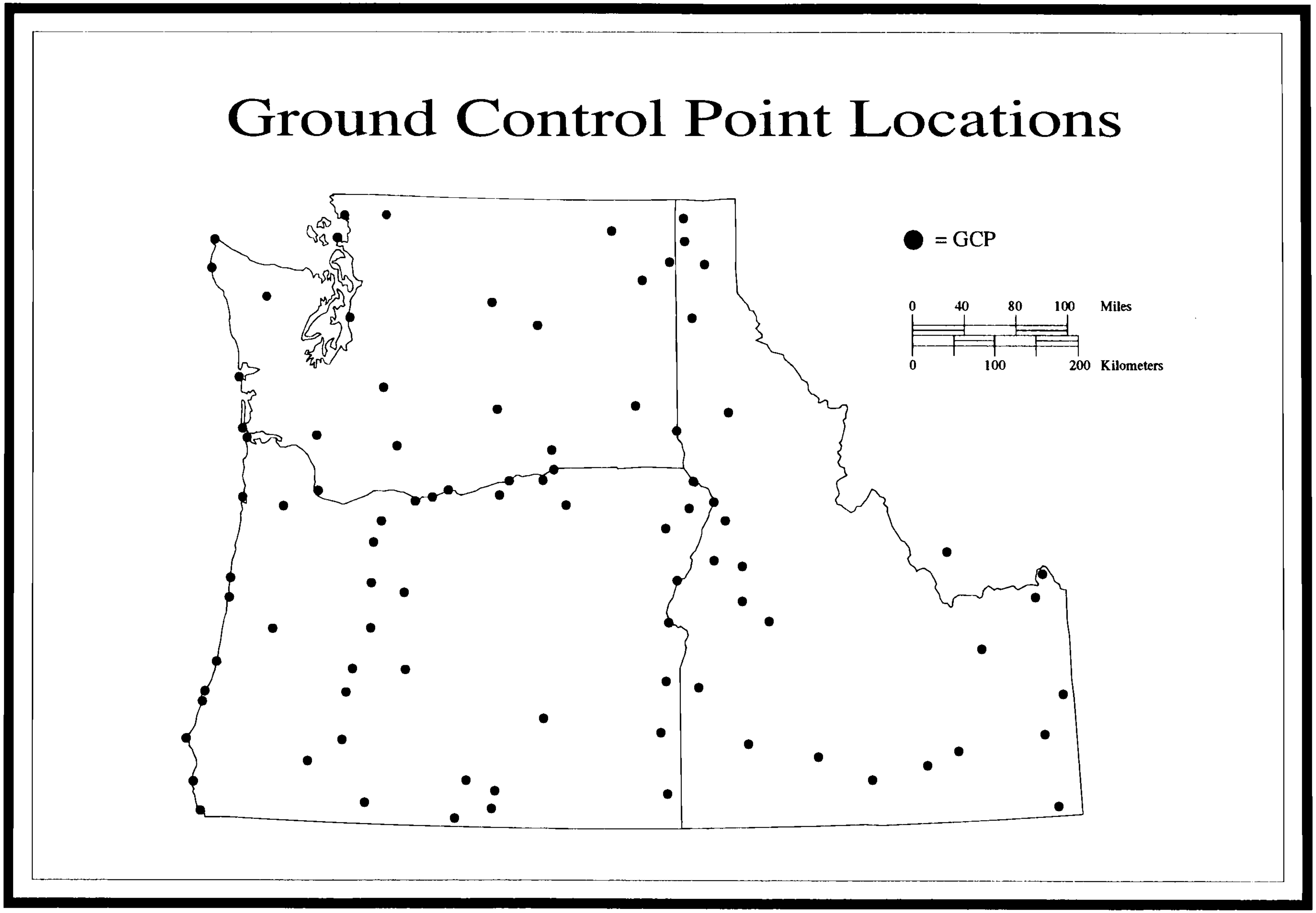


image. If much error was created during the rectification process, the image features would be greatly offset from the digitized overlay. The error between the digitized features and the rectified image varied between 1 and 2 pixels, an acceptable amount of displacement.

Area Delineation

Now that the AVHRR image was georeferenced and rectified to latitude and longitude coordinates, it was necessary to delineate the political study area boundary. This was accomplished by digitizing an Albers Equal-Area Conic Projection with standard parallels of 29.5 and 45.5 degrees North latitude (National Geographic Society, 1986). Once the PNW boundary outline was digitized, it was used to "cut" out the study area from the rectified image.

Biophysical Spectral Regionalization

The main objective of this study was to develop a methodology using AVHRR imagery as a tool for the delineation of relatively homogeneous spectrally distinct biophysical regions throughout the PNW. Delineation of the spectrally similar regions required that multiple band combinations be displayed at different times during the analysis. Numerous band combinations accentuated various features across the landscape: water, vegetation, topographic effects, soil, or land use. For a majority of the analysis, thermal infrared bands 4 and 5 were not used, due to their calibration uncertainties and spectrally dominating characteristics. Band values and groups of bands may be displayed singularly or in multiple combinations. In ERDAS it is necessary to specify a band value for each red, green, and blue component of the screen display. Most often the band combinations of 2,1,1 and 2,1,3 were utilized to study spectral variation between regions. The 2,1,1 display is a false color infrared composite image that typically portrays variation in vegetation photosynthetic vigor.

The 2,1,3 image adds a thermal component into the display. This thermal component seems to accentuate differences in landform, vegetation, and land use characteristics.

Once the rectified image was displayed, a module called DIGSCRN in ERDAS (1990a.) allowed for regional boundaries to be digitized directly from the computer monitor. Sections of the AVHRR image were magnified to aid in distinguishing areas of significant spectral variation. Two parameters used to differentiate regions throughout the delineation process included a minimum mapping unit area and the relative spectral contrast of an area when compared to adjacent regions. The minimum mapping unit area was maintained at approximately 0.01% of the image, or about 7,300 hectares. However, not all of the regions across the PNW with an area of approximately 7,300 hectares were delineated. Whether or not an area was delineated also depended on the relative intensity of its reflectance values in association with the reflectance values of the neighboring spectrally different regions. Regions with faint spectral discrepancies may have an extensive transitional boundary. Subjective judgment was then applied as to whether or not the region was delineated. Boundaries of spectrally distinct areas were then digitized for the entire PNW.

Once the biophysical spectral regions were delineated for the PNW, the digitized vector files were converted into raster polygons. Throughout the gridding process it was necessary to maintain the .0127 by .00901 degree cell size previously described.

In order to make the PNW image more representative of the actual landscape, it was necessary to identify permanent water bodies. A water template was created by extracting bands 1 and 2 (visible red and near-infrared) from the rectified PNW image. The 2 band image was then clustered into 20 classes. Clustering is "the process of generating signatures based on the natural groupings of pixels in image data when they are plotted in spectral space (ERDAS, 1990a., p. 378)." Water classes will typically have low red and near infrared mean spectral values. The clustering results are presented in Table 4. Once the classes containing permanent water bodies were identified, the image was made into a template by recoding all of the water features to a similar polygon value. This template was then used in an overlay procedure to extract all identifiable water bodies from the image. Now that the PNW image contained permanent water bodies, it was necessary to transform the scene into a standard map projection.

The regional file was initially georeferenced to latitude and longitude coordinates, a function of ERDAS default rectification parameters (ERDAS, 1990a). The geographic format is not a standard projection used within spatial analysis, but rather a method used to associate geographic coordinates with image features. Therefore, for cartographic purposes, it was necessary to transform the geographic coordinates into a conventional map projection. An Albers Equal-Area Conic Projection with standard parallels of 29.5 and 45.5 degrees North latitude was chosen for the output projection. ERDAS (1990a.) will not allow an image to be georeferenced to latitude and longitude coordinates unless it is displayed in the geographic projection, therefore, the Albers Equal-Area Conic projection was converted into metric units. The cell size was then transferred into the 1000 meter by 1000 meter pixel cell typically used with AVHRR analysis. The transformation from geographic coordinates to the Albers Equal-Area Conic projection yielded a total rms error of 0.60 with an "x" error of 0.48 and a "y" rms of 0.35 pixels.

Regional Labels

The labels assigned to the biophysical spectral regions of the PNW represent a hierarchy and aggregation of various regional naming schemes (Clarke et al., 1991; Gallant et al., 1989; Bailey, 1983; Lobeck, 1948; Raisz, 1941). Regional names are generally associated with the dominant physiographic characteristics of the area:

Table 4: Water Template Clustering Statistics

Cluster #	1	2	3	4	5
Image %	13.489	14.622	6.412	8.420	1.426
Band 1	64.87	68.15	66.93	59.58	54.82
Band 2	113.46	134.54	155.47	95.90	49.37
Cluster #	6	7	8	9	10
Image %	1.453	5.818	14.705	3.396	8.298
Band 1	72.38	83.94	101.56	106.42	119.95
Band 2	181.22	149.06	123.91	157.12	145.69
Cluster #	11	12	13	14	15
Image %	2.557	0.653	9.406	2.189	1.214
Band 1	91.20	79.59	84.42	135.02	111.10
Band 2	172.47	69.00	106.19	162.40	229.00
Cluster #	16	17	18	19	20
Image %	1.035	1.608	1.109	1.466	0.725
Band 1	111.79	99.38	135.93	118.34	125.08
Band 2	206.29	189.10	180.27	173.95	191.23

Columbia Plateau, Blue Mountains, Willamette Valley (Table 5). However, in some areas other characteristics such as vegetation, topography, or geology may dominate the landscape and would better describe a particular region: High Mountains, Ice -- Alpine, Urban, Basalt Flows (Table 6).

The biophysical spectral regions were identified and labeled by placing a qualifier in parentheses before the area description. The qualifier is designed to establish a hierarchical relationship between the spectral region and the larger physiographic province: (WV-1) Foothills = Willamette Valley Foothills Biophysical Spectral Region. The number in parentheses helps to differentiate other spectral regions within the larger province. The biophysical spectral regionalization qualifier names are representative of the dominant physiographic regions of the PNW environment. The biophysical spectral region maps were produced only after the regional naming scheme was developed and were then printed on a Textronix 4696 ink jet printer.

RESULTS

Two maps were produced as a result of this study: Spectral Physiographic Provinces of the PNW (Figure 3) and Biophysical Spectral Regions of the PNW (Figure 4).

The spectrally oriented physiographic regions of the PNW were constructed around major spectral associations and various regional naming schemes associated with the PNW environment. The Pacific Northwest was spectrally divided into 14 physiographic provinces (Table 5, Figure 3). Each province is an aggregation of the vegetative, land use, soil, geologic, and climatic variables that may be distinguished by examining AVHRR imagery.

Table 5: Spectral Physiographic Province Statistics

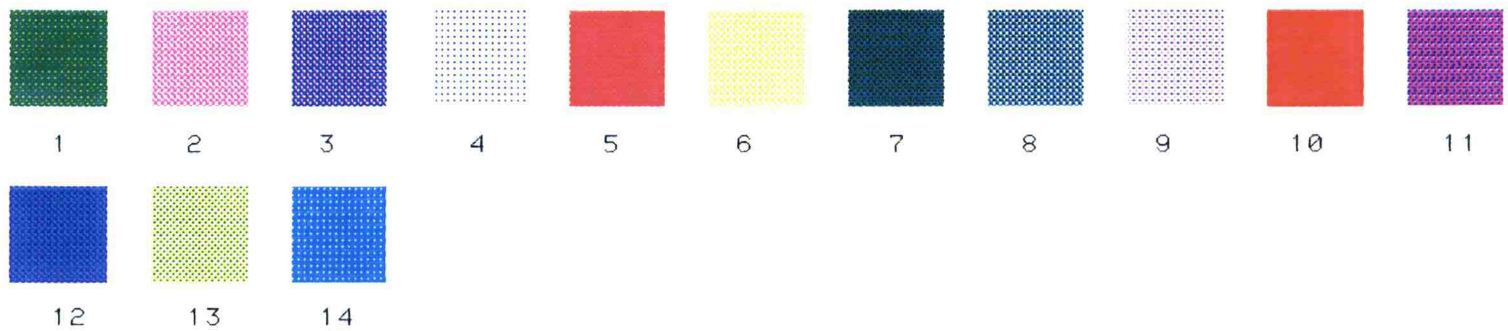
VALUE	POINTS	HECTARES	PERCENTAGE	REGION
1	65816	6581600.000	10.22	Coastal Province (CO)
2	15623	1562300.000	2.43	Willamette Valley (WV)
3	42981	4298100.000	6.68	Central Cascades (CC)
4	39853	3985300.000	6.19	Klamath Mtns. -- West Cascades (WC)
5	33204	3320400.000	5.16	Eastern Cascades (EC)
6	90035	9003500.000	13.99	Columbia Plateau (CP)
7	106850	10685000.000	16.60	Northern Rockies (NR)
8	75943	7594300.000	11.80	Blue Mountains (BM)
9	142082	14208200.000	22.07	High Desert (HD)
10	73	7300.000	0.01	Montana Valley (MV)
11	8001	800100.000	1.24	Middle Rockies (MR)
12	1786	178600.000	0.28	Wyoming Basin (WB)
13	1230	123000.000	0.19	Wasatch & Uinta Mountains (WU)
14	20285	2028500.000	3.15	Northern Basin & Range (BR)
TOTALS:		64376200.000	100.00	

Table 6: Biophysical Spectral Region Statistics

VALUE	POINTS	HECTARES	PERCENTAGE	REGION
1	58531	5853100.000	9.09	(CO-1) Coastal Province
2	1926	192600.000	0.30	(CO-2) Coastal Lowlands
3	2921	292100.000	0.45	(CO-3) Urban
4	2438	243800.000	0.38	(CO-4) River Valleys
5	6726	672600.000	1.04	(WV-1) Foothills
6	7648	764800.000	1.19	(WV-2) Plains
7	1249	124900.000	0.19	(WV-3) Urban
8	4563	456300.000	0.71	(CC-1) Ice -- Alpine
9	38210	3821000.000	5.94	(CC-2) High Cascades
10	208	20800.000	0.03	(CC-3) Basalt Flows
11	35966	3596600.000	5.59	(WC-1) Klamath Mtns - West Cascades
12	463	46300.000	0.07	(WC-2) Mt. St. Helens
13	3424	342400.000	0.53	(WC-3) River Valleys
14	18196	1819600.000	2.83	(EC-1) Foothills & Slopes
15	1847	184700.000	0.29	(EC-2) Lake Basins & Marshes
16	13161	1316100.000	2.04	(EC-3) Valleys & Lowlands
17	28748	2874800.000	4.47	(CP-1) Channeled Lowlands
18	36770	3677000.000	5.71	(CP-2) Channeled Uplands
19	9740	974000.000	1.51	(CP-3) Basins
20	5508	550800.000	0.86	(CP-4) Uplands
21	116	11600.000	0.02	(CP-5) Mutton Mtns.
22	9153	915300.000	1.42	(CP-6) Palouse
23	73252	7325200.000	11.38	(NR-1) High Mountains

Table 6 Continued

24	16030	1603000.000	2.49	(NR-2) Valleys & Trenches
25	16460	1646000.000	2.56	(NR-3) Low Elevation Mtns.
26	333	33300.000	0.05	(NR-4) Long Valley
27	775	77500.000	0.12	(NR-5) Sawtooth Mtns.
28	610	61000.000	0.09	(BM-1) High Blue Mtns.
29	31477	3147700.000	4.89	(BM-2) Middle Elevation Mtns.
30	2134	213400.000	0.33	(BM-3) Basins
31	41722	4172200.000	6.48	(BM-4) Uplands & Valleys
32	102951	10295100.000	15.99	(HD-1) High Desert
33	13540	1354000.000	2.10	(HD-2) High Desert Mtns.
34	2039	203900.000	0.32	(HD-3) High Desert Peaks
35	18333	1833300.000	2.85	(HD-4) Basins -- Fresh Water
36	2643	264300.000	0.41	(HD-5) Dry Barren Basins
37	2576	257600.000	0.40	(HD-6) Basalt Flows
38	73	7300.000	0.01	(MV-1) Foothills & Prairies
39	6410	641000.000	1.00	(MR-1) High Elevation Mtns.
40	1591	159100.000	0.25	(MR-2) Basins
41	1639	163900.000	0.25	(WB-1) Wyoming Basin
42	147	14700.000	0.02	(WB-2) Bear Lake -- Marsh
43	1230	123000.000	0.19	(WU-1) Mountains
44	13578	1357800.000	2.11	(BR-1) Basins & Valleys
45	6038	603800.000	0.94	(BR-2) Mountains
46	669	66900.000	0.10	(BR-3) Foothills
TOTAL:	643762	64376200.000	100.00	



The variable name is : Physiographic Spectral Regions of the PNW

VALUE	CLASS NAME
1	Coastal Province
2	Willamette Valley
3	Central Cascades
4	Klamath Mtns -- West Cascades
5	Eastern Cascades
6	Columbia Plateau
7	Northern Rockies
8	Blue Mountains
9	High Desert
10	Montana Valley
11	Middle Rockies
12	Wyoming Basin
13	Wasatch & Uinta Mtns
14	Northern Basin & Range

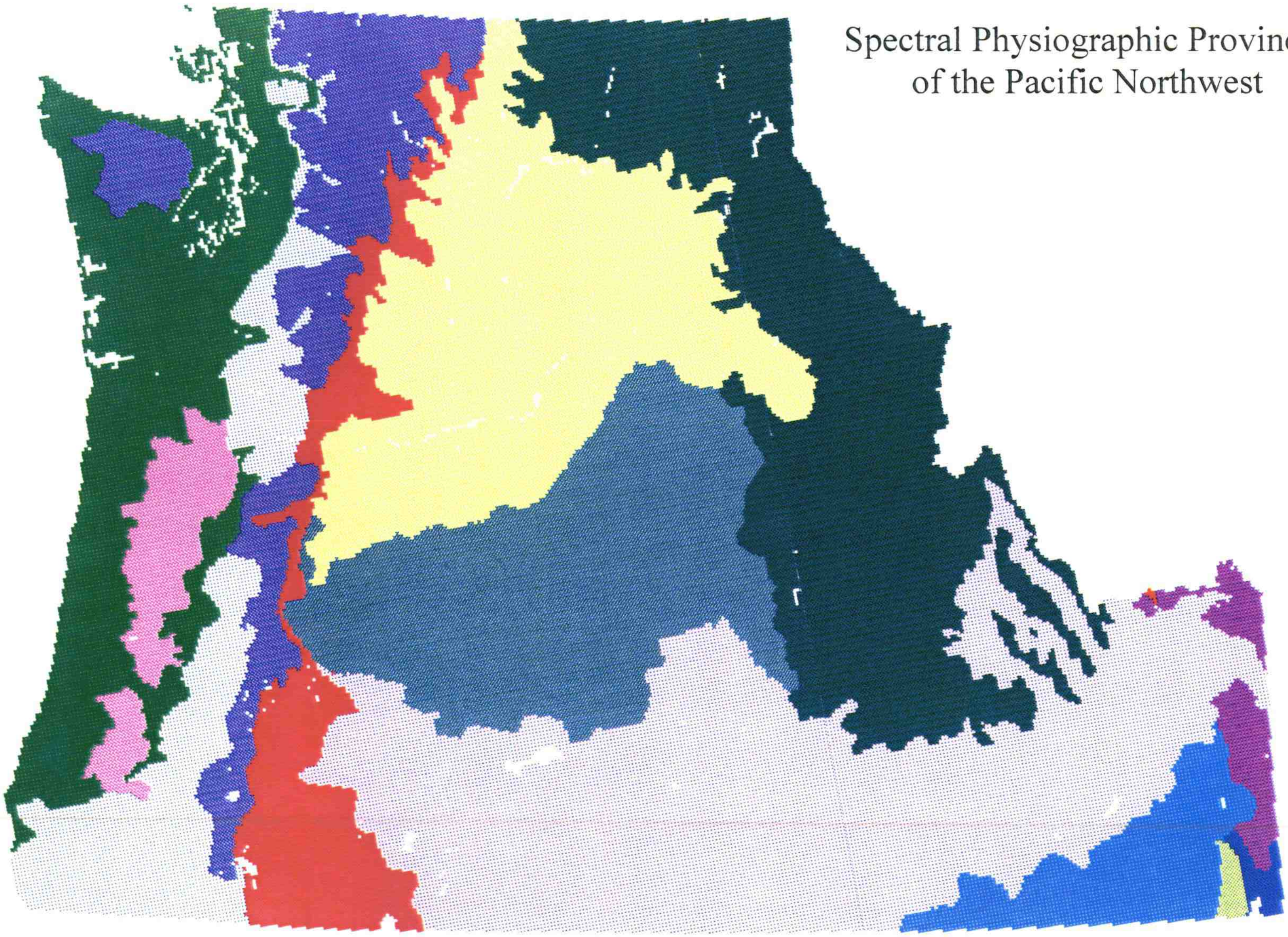
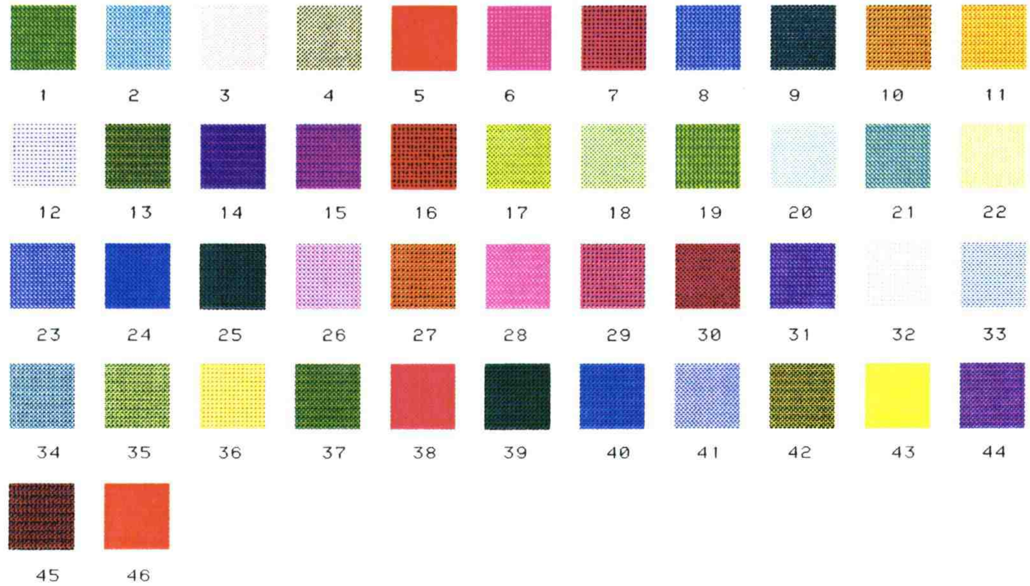


Figure 3.

Spectral Physiographic Provinces
of the Pacific Northwest



The variable name is : Biophysical Spectral Regions of the PNW

VALUE	CLASS NAME
1	(CO-1) Coastal Province
2	(CO-2) Coastal Lowlands
3	(CO-3) Urban
4	(CO-4) River Valleys
5	(WV-1) Foothills
6	(WV-2) Plains
7	(WV-3) Urban
8	(CC-1) Ice -- Alpine
9	(CC-2) High Cascades
10	(CC-3) Basalt Flows
11	(WC-1) Klamath - West Cascades
12	(WC-2) Mt. St. Helens
13	(WC-3) River Valleys
14	(EC-1) Foothills & Slopes
15	(EC-2) Lake Basins & Marshes
16	(EC-3) Valleys & Lowlands
17	(CP-1) Channeled Lowlands
18	(CP-2) Channeled Uplands
19	(CP-3) Basins
20	(CP-4) Uplands
21	(CP-5) Mutton Mtns.
22	(CP-6) Palouse
23	(NR-1) High Mountains
24	(NR-2) Valleys & Trenches
25	(NR-3) Low Elevation Mtns.
26	(NR-4) Long Valley
27	(NR-5) Sawtooth Mtns.
28	(BM-1) High Blue Mtns.
29	(BM-2) Middle Elevation Mtns.
30	(BM-3) Basins
31	(BM-4) Uplands & Valleys
32	(HD-1) High Desert
33	(HD-2) High Desert Mtns.
34	(HD-3) High Desert Peaks
35	(HD-4) Basins -- Fresh Water
36	(HD-5) Dry Barren Basins
37	(HD-6) Basalt Flows
38	(MV-1) Foothills & Prairies
39	(MR-1) High Elevation Mtns.
40	(MR-2) Basins
41	(WB-1) Wyoming Basin
42	(WB-2) Bear Lake -- Marsh
43	(WU-1) Mountains
44	(BR-1) Basins & Valleys
45	(BR-2) Mountains
46	(BR-3) Foothills

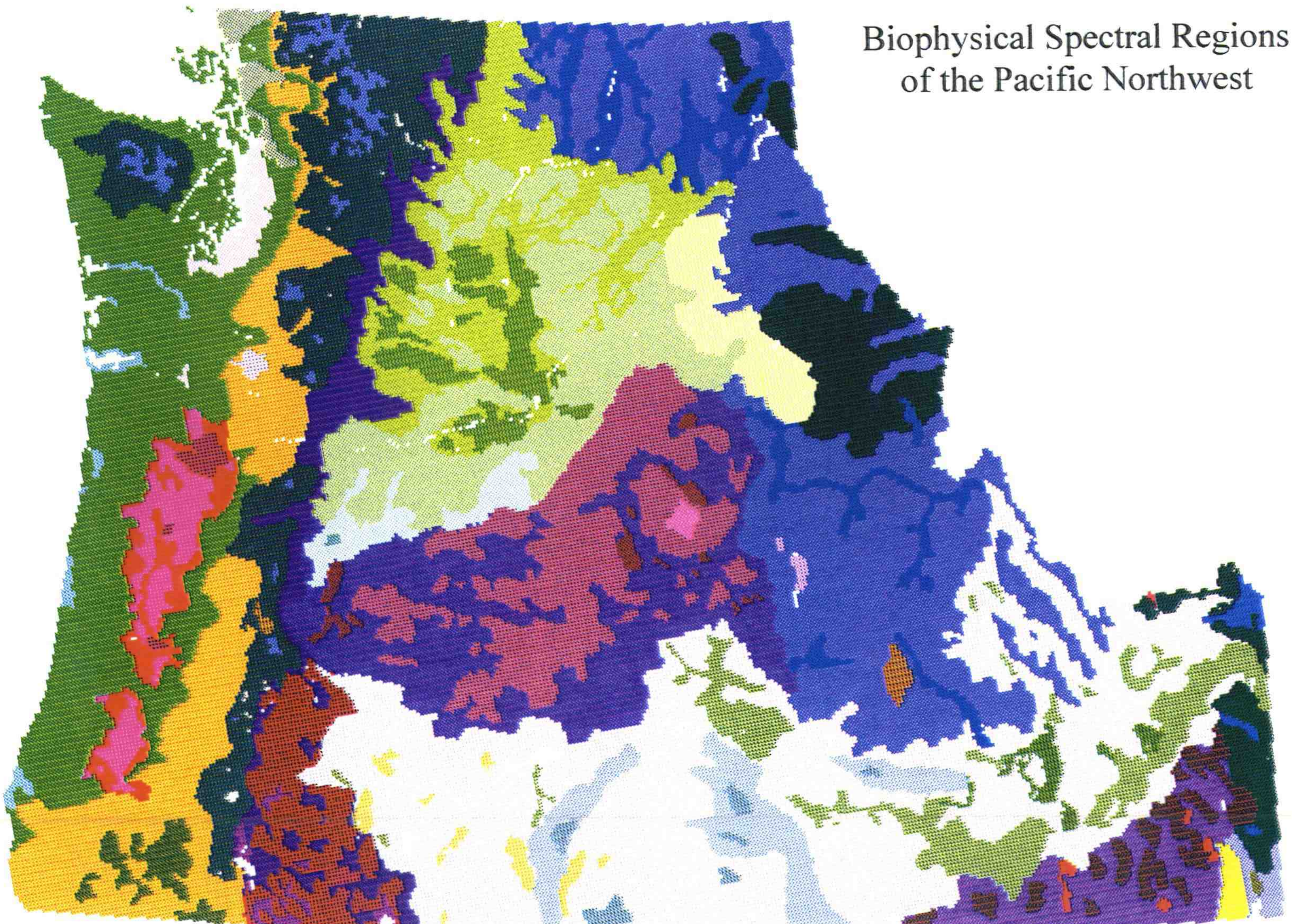


Figure 4.

Biophysical Spectral Regions of the Pacific Northwest

The PNW was partitioned into 46 biophysical spectral regions (Table 6, Figure 4). Each biophysical spectral region was representative of the relatively homogeneous, spectrally dominate features of the PNW landscape. Throughout Figure 4, the larger physiographic regions were identified through the use of similar hue progressions. Biophysical spectral regions containing similar color content, may be considered inclusive of the same physiographic province. The following list is an example of some of the factors that differentiated the various biophysical spectral regions:

- The coastal province was dominated by coniferous and mixed coniferous/deciduous vegetation.
- The Klamath Mountains and the western slopes of the Cascades were spectrally distinct from the remaining extents of the Cascade Mountains due to vegetative, topographic, and climatic influences.
- The desolated blast zone of Mount Saint Helens was spectrally independent from the adjacent landscape.
- The urbanized areas of Seattle-Tacoma, Longview, Vancouver-Portland, Salem, and Eugene-Springfield, were spectrally detectable. Urban areas such as Spokane and Boise were not distinguishable due to the similar high spectral reflectance values between the developed area and the surrounding arid landscape.
- The agricultural divisions of the Columbia Plateau were spectrally independent from one another. The Palouse in the eastern extents of the Plateau contained relatively high reflectance values due to the vast agricultural grasslands. The irrigated basins of the Columbia Plateau formed distinct spectral boundaries from the otherwise arid province.
- The crescent shaped network of irrigated basins of the Snake River Basin were in sharp contrast to the adjacent desert oriented landscape.

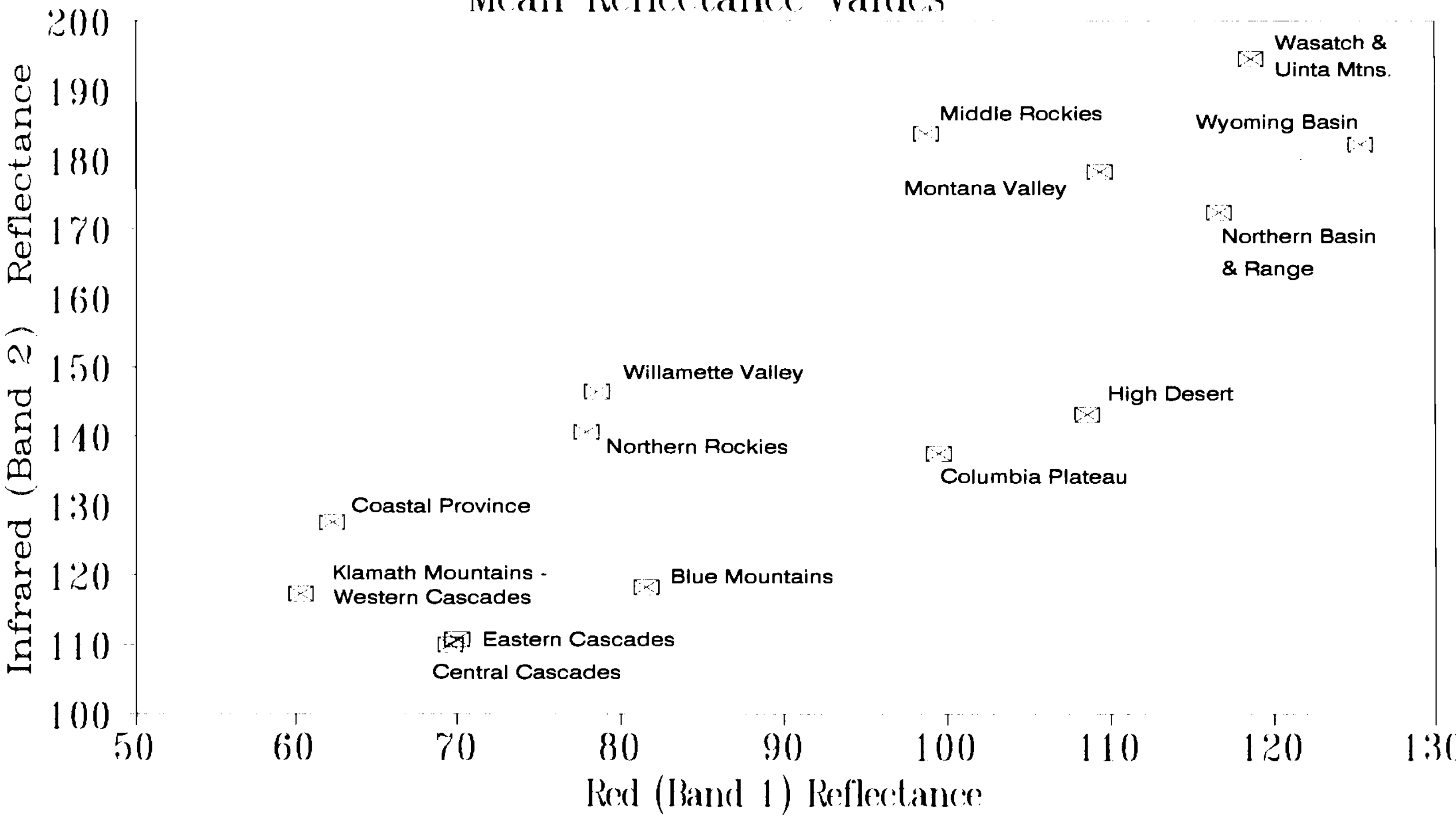
A scatter plot of red (band 1) and infrared (band 2) mean reflectance values shows the relative dispersion of the spectrally distinct physiographic regions of the PNW in spectral space (Figure 5). Red and infrared mean spectral values are typically plotted against each other to create a "tasseled cap formation"; a graphic measurement of the relative greenness and brightness across an image (Kauth and Thomas, 1976).

The spectral physiographic regions clumped into 7 clusters. Regions containing heavy conifer and mixed conifer/deciduous vegetation, such as the Coastal Province, Klamath Mountains - Western Cascades, and the Central and Eastern Cascades, are located in the lower portions of the scatterplot, indicating areas of relatively low "brightness" and moderate levels of "greenness". The Columbia Plateau and High Desert provinces appear further along the "soil line" indicative of the arid, desert oriented landscape. Provinces located across the eastern extents of Idaho: Middle Rockies, Montana Valley, Wasatch and Uinta Mountains, Wyoming Basin, and the Northern Basin and Range, are predominately clustered together in an area of relatively moderate greenness. The Willamette Valley and Northern Rocky provinces are in a position of high greenness, most likely due to the agricultural and deciduous vegetation influences.

DISCUSSION

Having discussed the variables incorporated into the regionalization processes and the biophysical spectral regionalization process itself, it is now important to examine how this methodology differs from ecoregion delineation.

Figure 5: PNW Spectral Dispersion
Mean Reflectance Values



Time Allocation

The compound process of ecoregion delineation as described by Omernik and Gallant (1986) and Bailey (1983) is quite lengthy; from several years for a continental scale, to several months for regional areas. The biophysical spectral regionalization process for the PNW took the following amount of time to complete:

• Image Rectification	3 - 4 weeks
• Biophysical Spectral Regionalization	2 weeks
• Final Checks and Map Production	1 - 2 weeks

Figures 3 and 4 yielded relatively similar results to the ecoregion work completed by Omernik and Gallant (1986), in considerably less time. Even though the ecoregions of the PNW (Omernik and Gallant, 1986) were used as a reference in the conceptualization of the biophysical spectral regionalization process, it was not used as a guide during spectral interpretation and delineation.

Image Content

Ecoregion maps are the product of combining multiple analog layers, such as geology, climate, topography, vegetation, soils, and land use, from a wide variety of sources printed at varying scales (Gallant, et al., 1989). In contrast, AVHRR imagery and the biophysical spectral regionalization process provided an ecologically integrated data source, in digital form, at a known scale. This digital format may be directly input into a resource manager's geographic information system (GIS) and immediately become part of a regionalization scheme for resource management purposes.

One distinct characteristic of AVHRR imagery, or any remotely sensed data, is that typically a dominate feature in the landscape will spectrally dominate the digital scene. Whereas, in some aspects of the ecoregion mapping process, the dominance of one feature across the landscape may hinder area delineation. This is due to the nature and character of remotely sensed data and the biophysical spectral regionalization process. The fact that a region has such dominating characteristics suggests that there is a certain amount of homogeneity throughout that particular system.

However, when an environmental attribute dominates the scene, it becomes difficult to spectrally detect any additional attributes in that same location. The EPA Environmental Research Laboratory in Corvallis, Oregon, has recently completed a map of subecoregions within the Washington and Oregon Coast Range (Thiele et al., 1993). This map is comprised of predominately geologic features. In the AVHRR image of the PNW, it was difficult to spectrally detect geologic features across the landscape, especially with spectrally dominate attributes, such as coniferous and deciduous vegetation. However, AVHRR imagery may detect surface geology features such as the basalt flows of McKenzie Pass, Oregon, or in the Craters of the Moon National Monument area in southern Idaho.

Spectrally distinct urban areas throughout the PNW were also identified. Urbanized regions are not typically delineated within ecoregion maps because they do not represent the potential, or natural landscape of an area. However, urbanized areas are quite dominate features of the landscape and their locations should be included into sub-regionalization schemes.

Applications

According to Bailey (1983, p. 365) "the purpose of ecological land classification is to divide the landscape into variously sized ecosystem units that have significance both for the development of resources and for conservation of environment." Output from the biophysical regionalization process could be incorporated into a variety of regional natural resource management applications, most notably, homogeneous stratification schemes. Once a spectrally oriented study area is identified, it may be incorporated into a wide variety of analysis and management schemes: vegetation classification, wildlife habitat study, land use change studies, or ecosystem evaluation. Biophysical spectral regionalization procedures combined with the integration of other remotely sensed data sources, geographic information system analysis, and other environmental databases, could provide resource managers with a more ecological and systematic perspective on the PNW environment.

One methodological and scientific advantage that the biophysical spectral regionalization process has over current methods of regionalization is that it is based on digital data. Omernik and Gallant (1990, p. 941) state "the drawback of a qualitative approach (ecoregionalization) is that two different investigators are not likely to arrive at identical regional boundaries." Even though a certain amount of subjectivity will always be involved whether or not one uses a quantitative or qualitative data set, an investigator may look at the AVHRR scene and replicate relatively similar regional boundaries based on similar or different spectral reflectance values. With manual methods of regionalization, it is almost impossible to identify and detect where or why a particular boundary was drawn.

Throughout this project, the delineation of regional boundaries across the PNW using AVHRR imagery has fostered both support and criticism from various groups and individuals. The criticism stems from the thought that biophysical spectral regionalization is meant to replace traditional methods of ecoregion delineation. The process of spectral regionalization, as described in this paper, was designed to provide an environmentally integrated, time efficient data source that may be used separately for ecosystem management applications, or to be incorporated as an ancillary data layer in the ecoregion mapping process.

When discussing the methodology of this project it was frequently questioned as to why a multi-date composite NDVI image was not used for regional delineation. A NDVI is the ratio between [(near infrared - visible red)/(near infrared + visible red)], and is designed to monitor phenomena such as, photosynthetic radiation, leaf area, annual primary productivity, and vegetation biomass (Goward, et al., 1991.). By using this type of measurement for regional delineation, vegetative characteristics would dominate the scene. Data linking vegetation, soil, geology, climate, and land use would be minimized. By using one single-date AVHRR image, the researcher examines a more true representation of the landscape, rather than a multi-date false composite or ratio image, which presents a transformed view of the region.

Procedural Limitations

Using ERDAS (1990a.) for the digital image processing portion of the biophysical spectral regionalization process was satisfactory. The main limitation experienced when using ERDAS involved the digitizing process, in particular the DIGSCRN module. Digitizing within ERDAS revolves around a hierarchical procedure; the most recently digitized boundary will override previously digitized boundaries, if they overlap. This organization makes it difficult to come out of a digitizing session with a complete vector file that may be used for further analysis or to export to another GIS.

Another inconvenience associated with the DIGSCRN routine was that the module only allowed a single polygon or vector to contain 100 vertices instead of the 5000 vertices that may be acquired when digitizing from a tablet (ERDAS, 1990a.). This problem was resolved by appending multiple screen digitized files into one complete regional boundary file. When using the DIGSCRN module, although convenient for regional delineation, it becomes awkward having to append so many *.DIG files, with overlapping vector lines. In order to obtain complete vector boundary files, it may be necessary to digitize in another software package.

Other limitations encountered include restrictions associated with the GNIS method of GCP location and the devising of a standardized naming convention for regional identification. The main disadvantage associated with GCP location using the GNIS index was that the location of the GCP was restricted by the feature names located on the topographic sheets. If there is no particular name at a point of interest, this method of GCP location may not be the appropriate choice.

Future Directions

Continuing research efforts to refine the biophysical spectral regionalization process could include:

- Ground truth procedures to test and validate the biophysical spectral regions of the PNW, which would assist in the acceptance of the regionalization procedure into the research and resource management communities.
- Utilizing digital elevation models (DEMs) in conjunction with AVHRR imagery to bring a 3-dimensional elevation/topographic component into the analysis. The satellite image may be draped over the DEM and then incorporated into the regionalization scheme. Elevation and topographic effects play integral roles in influencing the ecological environment and could potentially create a totally new outlook for environmental and ecological researchers as well as for resource managers.
- Scale limitations inherently associated with AVHRR imagery may possibly be eliminated by using larger scale imagery, such as Landsat Thematic Mapper (30 meter resolution) or SPOT Multi-spectral Scanner (20 meter resolution), for the further sub-delineation of the biophysical spectral regions.

- Upcoming innovations and advancements in satellite sensor technology, such as EOSAT's Landsat 6 satellite (15 meter resolution), scheduled to be launched in the summer of 1993, along with the sensors scheduled to be placed upon NASA's Earth Observation System (EOS) platform in the late 1990s, will allow researchers to dynamically examine the earth's aquatic and terrestrial features like never before. Two of the remote sensing platforms that will lead resource management in new directions include the High Resolution Imaging Spectrometer (HIRIS) and the Shuttle Imaging Spectrometer Experiment; global coverage with 128 spectral channels at 30 meter resolution (Lillesand and Kiefer, 1987, p. 469).

SUMMARY

This study has demonstrated a procedure for delineating biophysical spectral regions across the Pacific Northwest using NOAA AVHRR imagery. The biophysical spectral regionalization process has been shown to be different from ecoregionalization methodologies in several important aspects: time allocation, image content, and applications. This biophysical spectral regionalization methodology involved several steps: obtaining imagery, georeferencing, rectification, area delineation, regionalization, and regional labeling. As a result of this methodology and study of biophysical spectral regions, two maps were produced: Spectrally Oriented Physiographic Regions of the Pacific Northwest and Biophysical Spectral Regions of the Pacific Northwest. This methodology has promising applications for the development of sound and integrated natural resource management plans. Timely and efficient interpretation of multi-band satellite imagery, in a systematic format, has presented resource managers with a new alternative and orderly process for area regionalization.

REFERENCES

AutoCAD, 1992. Release 12. Autodesk, Inc. Sausalito, California.

AutoScript, 1992. Version 5. Preco Industries, Inc.

Bailey, R.G. 1983. Delineation of ecosystem regions. Environmental Management. 7(4):365-373.

Bernert, J.A., Eilers, J.M., Freemark, K.E., Ribic, C., Smith, J., and Ripple, W.J. In press. Regionalization of the western corn belt plains ecoregion. Agricultural Research to Protect Water Quality. Conference Proceedings. Ankeny, IA.

Cicone, R.C. and M.D. Metzler. 1984. Comparison of Landsat MSS, Nimbus-7 CZCS, and NOAA-7 AVHRR features for land-use analysis. Remote Sensing of Environment. 14: 257-265.

Cihlar, J., St.-Laurent, L., and J.A. Dyer. 1991. Relation between the normalized difference vegetation index and ecological variables. Remote Sensing of Environment. 35:279-298.

Clarke, S.E., D. White, and A.L. Schaedel. 1991. Oregon, USA, ecological regions and subregions for water quality management. Environmental Management. 15(6): 847-856.

Crowley, J.M. 1967. Biogeography. Canadian Geographer. 11:312-326.

ERDAS, 1990a. Earth Resource Data Analysis System, Vers. 7.4, ERDAS, Inc. Atlanta, Georgia.

ERDAS, 1990b. Field Guide. Earth Resource Data Analysis System, Vers. 7.4, ERDAS, Inc. Atlanta, Georgia.

Gallant, A.L., T.R. Whittier, D.P. Larsen, J.M. Omernik, and R.M. Hughes. 1989. Regionalization as a tool for managing environmental resources. EPA/600/3-89/060.

Goward, S.N., Markham, B., Dye, D.G., Dulaney, W., and J. Yang. 1991. Normalized difference vegetation index measurements from the advanced very high resolution radiometer. Remote Sensing of Environment. 35:257-277.

Griffith, G., 1993. Personal Communication. EPA Environmental Research Laboratory, Corvallis, Oregon.

Isaacson, D., 1993. Personal Communication. Environmental Remote Sensing Applications Laboratory, Corvallis, Oregon.

Jensen, J.R. 1986. Introductory digital image processing: a remote sensing perspective. Prentice-Hall, New Jersey.

Kauth, R., and Thomas, G. 1976. The tasseled-cap -- a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. Machine Processing of Remotely Sensed Data, Symposium Proceedings. Purdue University/LARS, West Lafayette, IN. In:Cicone, R.C. and M.D. Metzler. 1984. Comparison of Landsat MSS, Nimbus-7 CZCS, and NOAA-7 AVHRR features for land-use analysis. Remote Sensing of Environment. 14: 257-265.

Kelly, G., and Hood, J. 1991. AVHRR conterminous United States reference data set. Technical Papers, Remote Sensing. ACSM-ASPRS Convention. Baltimore, MD. 3:232-239.

Kimerling, A.J., and Jackson, P.L. 1985. Atlas of the pacific northwest. Oregon State University Press, Corvallis, Oregon.

Lillesand, T.M. and R.W. Kiefer. 1987. Remote sensing and image interpretation. Wiley & Sons, New York.

Lobeck, A.K. 1948. Physiographic provinces of North America. Map (scale 1:12,000,000). The Geographical Press, New Jersey.

Loveland, T.R., J.W. Merchant, D.O. Ohen, and J.F. Brown. 1991. Development of a land-cover characteristics database for the conterminous US. Photogrammetric Engineering and Remote Sensing. 57(11):1453-1463.

MicroCAM. 1992. Version 3.1. Annapolis, MD.

National Geographic Society. 1986. The Pacific Northwest. Map (scale 1:2,216,000). Albers Conic Equal-Area Projection.

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Text and Map supplement, scale 1:7,500,000. Annals of the Association of American Geographers. 77(1):118-125.

Omernik, J.M. and A.L. Gallant. 1986. Ecoregions of the Pacific Northwest. Map (scale 1:2,500,000). EPA/600/3-86/033. U.S. Environmental Protection Agency, Corvallis, Oregon, 39 pp.

Omernik, J.M., and A.L. Gallant. 1990. Defining regions for evaluating environmental resources. In:Global Natural Resource Monitoring and Assessments. Proceedings of the International Conference and Workshop, Venice, Italy. pp. 936-947.

Paltridge, G.W. and J. Barber. 1988. Monitoring grassland dryness and fire potential in Australia with NOAA/AVHRR data. Remote Sensing of Environment. 25:381-394.

Peters, A.J., Reed, B.C., and D.C. Rundquist. 1992. A technique for processing NOAA-AVHRR data into a geographically referenced image map. Photogrammetric Engineering & Remote Sensing. 58(5):569-571.

Raisz, E. 1941. Landforms of the northwestern states. Map (no scale).

Thiele, S.A., Killsgaard, C.W., and Omernik, J.M., and S.M. Pierson. 1993. Draft ecoregions and coast range subregions of Oregon and Washington. Map (scale 1:2,200,000). United States Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon.

Thiele, S.A., Killsgaard, C.W., and J.M. Omernik. 1992. The subdivison of the coast range ecoregion of Oregon and Washington. Draft.

Townshend, J., Justice, C., Li, W., Gurney, C., and J. McManus. 1991. Global land cover classification by remote sensing: present capabilities and future possibilities. Remote Sensing of Environment. 35:243-255.

Tucker, C.J., Townshend, J.R.G., and T.E. Goff. 1985. African land-cover classification. Science. 227(4685):369-375.

USGS. 1962. State of Washington. Map (scale 1:1,000,000). Washington, D.C.

USGS. 1966. State of Oregon. Map (scale 1:1,000,000). Washington, D.C.

USGS. 1968a. State of Idaho. Map (scale 1:1,000,000). Washington, D.C.

USGS. 1968b. State of Idaho. Map (scale 1:500,000). Washington, D.C.

USGS. 1981a. Idaho Geographic Names. Branch of Geographic Names. Reston, Virgina. Vol. 1-2.

USGS. 1981b. Washington Geographic Names. Branch of Geographic Names. Reston, Virgina. Vol. 1-2.

USGS. 1982a. State of Oregon. Map (scale 1:500,000). Washington, D.C.

USGS. 1982b. State of Washington. Map (scale 1:500,000). Washington, D.C.

USGS. 1983. Oregon Geographic Names. Branch of Geographic Names. Reston, Virgina. Vol. 1,2,3.

Wiken, E. 1986. Terrestrial ecozones of Canada. Environment Canada. Ecological Land Classification. Series No. 19. Ottawa, Canada. 26 pp. In: Thiele, S.A., Killsgaard, C.W., and J.M. Omernik. 1992. The subdivison of the coast range ecoregion of Oregon and Washington. Draft.