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Jay S. Noller

Predictive Soil Mapping (PSM) has recently become an attractive method for soil scientists wishing to develop a more objective and efficient approach to mapping soils. Due to the potential PSM has for reducing the effort to produce soil maps, as well as its ability to improve the classification accuracy of soils, this method has peaked the interest of agriculturalists and land managers desiring quantitative information about soils and the landscape. In this study, PSM is applied in the Fremont National Forest (NF) of south-central Oregon, where an updated soils map and National Hierarchy Landtype Association (LTA) map are needed.

Decision-tree analysis (DTA) is a PSM technique and was used to derive the landscape model to produce both maps needed for the study area. DTA aided in the process of identifying errors in the original Soil Resource Inventory (SRI) map of the Fremont NF and in developing a corrected predictive soils map of the forest. Once a predicted soils map of the forest was made, an LTA map using the newly predicted soil boundaries and landforms was produced and designed for display at a scale of 1:100,000.

Both the accuracy of DTA prediction rulesets and a discrete multivariate technique, the kappa analysis, were employed to assess the accuracy of the predictive soils maps of the Fremont NF. Maps produced with training data from the original SRI of the forest yielded results between the lower sixtieth to mid eightieth percentiles, and maps produced with corrected training data yielded results in the lower ninetieth to upper ninetieth percentiles. Kappa for predictive maps using modified training data showed strong agreement between ground-truth maps and predicted maps.

Predictive Mapping for the Delineation of Landtype Association Units in the Fremont National Forest, Oregon

by

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

Melanie R. Malone, Author

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INTRODUCTION

1.1 Overview

Recently, new methods for mapping soils and other landscape features have become increasingly important worldwide from increased demand for accurate information in agriculture and ecological models (Scull et al., 2003). Though this demand has increased, it has proven difficult to provide these maps, as they either do not exist or do not provide the amount of information needed in many projects. For example, even the most recent U.S. General Soil Map (STATSGO2) of the conterminous United States is at a scale of 1:250,000 (NRCS, 2008). While this scale is useful for and intended for regional, multi-state, river basin, and multi-county resource planning, it is not always useful for smaller research areas, where finer resolution maps are needed.

A similar predicament occurs in the area of interest for this study, the Fremont National Forest (NF), where there is a need for a soil and Landtype Association (LTA) map of the forest. LTA maps and their descriptions are largely used in the land management planning process as analysis units to organize broad areas by suitability, identify restoration priorities, and serve as a coarse filter for protecting biodiversity (Almendiger et al., 2000). Soil and LTA mapping in the Fremont NF is important, because of the implications for environmental management. Here, concerns about how to effectively manage the soils and the land that comprises the forest have been present prior to and since its first boundaries were drawn in 1908 (Lawrence, 1955).

The Fremont NF is located in an area of Oregon where the availability of natural resources is limited and requires careful land management practices. One area of major concern is the availability of water, which is limited in the dry and semi-arid climate of the forest. Because the characteristics of soil and water availability are closely intertwined, how soils are managed in the forest, which supplies over 900,000 acre feet of water per year, is extremely important (USDA, 1975). Sustainable timber production in the forest is of concern as well. Many of the small, rural towns surrounding the Fremont NF rely on timber mills that are supplied by the forest. Unfortunately, due to declining harvest levels, several of these mills have been forced to close, which has had a significant effect on the already poor economy of the area (Baker and Brumm, 2004).

Though a Soil Resource Inventory (SRI) of the forest was created in 1979, this inventory was only meant to be a starting point by which the soils and the landtypes in the region were classified. For any project or study that needed more detailed information, additional intensive on-site inventories and interpretations were recommended (Wenzel, 1979). Therefore, for this study, a predictive mapping approach was taken in order to improve upon the first effort of mapping the Fremont NF and to provide updated soils and LTA map units for the forest.

Mapping soils or other features in landscapes covering large areas with acceptable precision and cost requires the development of specific methods that use available information and minimize sampling of reasonable size (Lagacherie and Voltz, 2000). One technique used in this study, predictive soil mapping (PSM), exploits the relationship between environmental variables and soil properties, which is then applied to a geographic database to create a predictive map (Scull et al., 2003). The ability to predictively map soils remained elusive until the development of more advanced technologies became available in the past several decades, and these will be discussed in the next section.

Prior to these technological developments, soil surveying relied solely on the decisions made by soil surveyors, the accuracy of which depended heavily on experience in the field and knowledge of the area. This knowledge and experience, however, was often intangible and not very useful to other soil surveyors seeking an objective strategy to map soils (Burrough et al., 1997). Therefore, predictive mapping has become an attractive approach for many scientists and surveyors alike, as data layers acting as proxies for environmental variables in a given study area can be chosen based on research.

1.2 Context for Study

Due to the fact that this study is focused on using a predictive model to map soils, which in turn influences LTA unit delineations, it is appropriate to discuss the validity of using this method for these tasks. The first topic that needs to be addressed is how predictive soil mapping (PSM) compares to traditional methods of soil survey. Traditional soil surveying is intended to provide information for soil or land management practices (McBratney et al., 2000). The surveyor of an area develops a mental model of the landscape and its relationships to its soils, creates hypotheses about these relationships, and then field-checks an area that has been classified with this approach (Wilding, 1985). Often, the complex and variable nature of soil patterns in the landscape complicates the labor-intensive process of collecting and presenting soil survey (Scull et al., 2003). To reduce these complications, the surveyor must be able to ascertain the patterns of soil distribution throughout the area of study. However, as mentioned in the previous section, the decisions used to guide the individual soil surveyor's landscape model are often subjective (Lagacherie, 1995). Therefore, the final product of a soil survey is usually a soil map that has unknown assumptions, limitations, and accuracy (Burrough et al., 1971 and Dijerkman, 1974).

Due to increasing awareness of environmental pollution and the need for accurate landscape models, more quantitative soil information is being required than qualitative soil survey methods can offer (McBratney et al., 2000). In order to accommodate this growing need for quantitative soil information, the field of pedometrics has been gaining wide use among soil scientists. Pedometrics involves the use of mathematical and statistical models to study soils (Webster, 1994). It is out of this field that PSM has emerged, which also uses numerical or statistical models to collect soil data (Scull et al., 2003).

Traditionally, Jenny's State Factor soil-forming model (1941) has been the backbone of the theory used for PSM. However, PSM has been constrained by problems associated with this model of soil genesis in the past. The first problem was that the mathematical equations derived from the model were unsolvable (Huggett, 1975). The second problem was that there were no data layers representing the soil-forming factors in the model that were available. These problems were overcome by technological advances in the past few decades (McKensie et al., 2000). Technological advancements include improvements made to such areas as computational powers, remote sensing technology, digital elevation models (DEMs), classification and regression trees, and geographic information systems (GIS).

Remote sensing data are commonly used in PSM analyses, because they provide a spatially contiguous, quantitative measure of surface reflectance, which is related to some soil properties (Agbu et al., 1990). Particle size, surface mineralogy, and moisture are just some of the soil characteristics which can be detected by spectral reflectance (Irons et al, 1989). However, remote sensing of soil is usually limited to areas of low or sparse vegetation, as is present in drier semi-arid and arid environments. Interferences caused by vegetation reflectance, terrain, or cloud cover may occur as well (Dobos et al., 2006). Nonetheless, many comprehensive studies using remote sensing data for soil classification and mapping have been conducted (Stoner et al., 1980; Henderson et al., 1992). These studies and others like them are completed using photo-interpretation or digital image processing supplemented with ancillary information such as thematic maps or vegetation cover (Wilcox et al., 1994).

GIS are useful components of PSM as well. GIS technology is used to encode, store, analyze, and display information obtained through GPS and remote sensing data collection (Burrough, 1986). The introduction of GIS into the soil science community has provided many new opportunities. GIS technology enables users to transform mapped data into digital data representations, which are linked with databases and subsequently numerous processing capabilities across the landscape (Berry et al., 2005). Within GIS, two main data models exist, which are vector and raster. Raster data refers to data layers used to represent surfaces with continuous numeric values, such as slope or aspect. Vector data are intended to represent discrete features with distinct boundaries, such as gridlines.

Both raster and vector data models have a variety of uses in spatial analysis, but the raster has become one of the most widely used data models for PSM (Scull et al., 2003). Raster data models produce a field-view representation of the landscape in a continuous grid of rectangular cells associated with specific values. They are routinely used to manage numerous forms of environmental information, one of the most important of which for PSM are DEMs. DEMs are digital records of land surface elevations and were one of the first widely available forms of digital geographic information used to study soil attributes (Odeh et al., 1991; Moore et al., 1991; Mackay and Band, 1998). As a form of digital data that was achieved by numerous processing and modeling steps, all DEMs contain some source of error. The most common attempts to quantify DEM error usually involves some form of root mean square error analysis (RMSE) (Li, 1988; Shearer, 1990). A significant amount of research has been performed on DEM error that has been concerned with its identification, description, visualization and modeling as well (Agumya and Hunter, 1999; Devillers et al. 2002; Veregin, 1999).

Even with all of this research interest in DEM error, however, no study conducted has ever performed a complete inventory of the errors accumulating from the beginning to the end of the DEM modeling process. It is generally accepted that DEM error is not any worse than error in other forms of digital geographic data, as all datasets contain error which can propogate to dependent operations (Fisher and Tate, 2006). DEMs are widely accepted among researchers because they have become a data format with which many users are familiar. As a recognizable form of data, it is easier to share and convey information to a wide group of researchers. Furthermore, DEMs are in a format which is closely associated with the mathematical concepts of surface modeling (Fisher and Tate, 2006). This format enables relationships to be constructed with a variety of datasets.

Surface modeling, which maps the data pattern of a single variable, is important for PSM. It is further supplemented by spatial data mining procedures that seek to reveal relationships within and among mapped data layers, such as the ones generated through surface modeling (Berry et al., 2005). Spatial data mining techniques can be applied to predictive models, and one form of this application is what is known as a classification or decision tree analysis (DTA). The purpose of DTA is to design a set of predictive rules, which can be applied to a geographic database to predict the value of a response variable (Michaelsen et al., 1994). DTA is becoming more popular among those trying to develop prediction rules for mapping that can be quickly assessed and repeated (Cialla et al., 1997). Several studies have been conducted using DTA such as Lagacherie and Holmes (1997), Cialella et al. (1997), Ellis (1996), and McKensie and Ryan (1999). Though concerns have arisen that the use of DTA sometimes results in a stepped prediction surface (usually caused by predictor variables at different resolutions (Gessler, 1996)), the benefits of its use outweigh the drawbacks for many scientists. These benefits are numerous and the most significant of which, as defined by Moore et al. 1991, are because 1.) DTA is easier to interpret when explanatory variables are both nominal and continuous, 2.) DTA deals more satisfactorily with missing data values and outliers, 3.)

DTA does not make any assumptions about data distribution, and 4.) DTA it is easily updateable when more data are collected.

Once a predictive map has been produced using DTA, a classification scheme to determine its accuracy may be employed (Liu et al., 2006). A variety of methods have been developed to assess the accuracy of classified maps (Congalton, 1991; Stehman and Czaplewski, 1998). One such method is performed by the use of an error matrix, also known as a confusion matrix (Story and Conglaton, 1986; Smits et al., 1999). A confusion matrix provides the calculations of specific accuracy measures such as the overall accuracy, and user's and producer's accuracies (Congalton, 1991). Overall accuracy represents the total number of correct pixels in an image divided by the total number of pixels in the confusion matrix. Producer's accuracy indicates the probability of a certain pixel being correctly classified, and user's accuracy indicates the probability that a pixel classified in the map is represented on the ground (Congalton, 1991). These accuracy measures have become widely used by those analyzing predicted soil maps.

Though a variety of models involving both traditional and PSM techniques have been tested, there is no consensus on how to model soils in the landscape (Scull et al., 2003). It has been suggested that failure to come up with a widely accepted model is due to the fact that soil science is a relatively new discipline (Johnson and Watson-Stegner, 1987). Future studies involving the improvement of soil data information in the landscape will be needed before such a model is available.

1.3 Hypotheses

This study is conducted to test the utility of a PSM approach to forest-wide inventory of natural resources, particularly as a tool to enhance or replace conventional methods. As such, the PSM approach remains unknown as a surrogate or aide in support of the National Hierarchy. This study seeks to test just this.

I hypothesize that 1.) Whereas, a traditional soil survey is valuable for the initial classification map of soils, a more accurate map of the forest will be produced with the addition of a predictive-soil mapping approach. 2.) Because the soils map will be improved, LTA units which are based on soil boundaries and other landscape features, will correspondingly be more accurate than if based on using the originally mapped landtypes of the Fremont NF.

The primary objectives of this thesis were twofold. The first objective was to determine which environmental variables in the Fremont NF most accurately predicted soils in the forest, and to develop a method by which predictions could be performed consistently. This was done by applying a predictive mapping approach, which revealed the relationships between the soils and the environmental data used to predict them in the forest. The second objective was to use the predicted soils in conjunction with a constructed landform map to derive LTA map units. This objective was completed after all predictions had been completed and after landscapes features that could comprise an LTA had been analyzed.

The accuracy of the original SRI soil survey map and a predicted map produced with modified training data are tested by a DTA prediction method and the use of a discrete multivariate technique, the kappa analysis. If the first hypothesis is not proven, the DTA prediction accuracy of the original SRI map will be higher than the prediction accuracy of the predicted map. Subsequently, the kappa coefficient will express greater agreement between data layers predicted with training data from the original SRI map than data layers predicted with modified training data. Furthermore, if the first hypothesis is disproved, the second hypothesis will be as well, and an LTA map of the forest will be more accurate if constructed on the basis of the original SRI landtypes.

STUDY AREA

2.1 Overview

The study area is in the Fremont portion of the Fremont-Winema National Forests of south-central Oregon (Figure 1). The forest spans over 1.2 million acres in Klamath and Lake Counties, in an area where the high desert plains of eastern Oregon meet the Cascade Mountain Range. Two Major Land Resource Areas (MLRAs) comprise the forest (Figure 2). These MLRAs are MLRA 6, the formal name of which is *Cascade Mountains, Eastern Slope*, and MLRA 21, known as the *Klamath and Shasta Valleys and Basins* (NRCS, 2006). MLRAs are made up of geographically associated land-resource units (LRUs), and LRUs are usually coincident with general state soil maps. In determining MLRA boundaries, considerations are made for statewide agricultural planning, interstate, regional, and national planning. Additionally, landscape conditions, soils, climate, human activity, and other natural resource information are taken into consideration when delineating boundaries (NRCS, 2005).

The initial project goal was to digitally map and delineate LTA units for the entire forest. However, this objective was changed to complete these tasks for the majority, but not all of the forest. The first area not analyzed is the northernmost section of the Fremont NF, located in the area known as the pumice plateau. This portion of the forest was not analyzed for this study, because it is the subject of the work of Slevin, PhD candidate in Soil Science (in preparation). Slevin is mapping in this region of the forest, where soils are heavily influenced by Mount Mazama pumice. The second area that was not mapped was the most eastern extent of the Fremont NF, which lies east of Lakeview on the Warner Mountain Range. After running several predictions and field-checking the soils and landforms in this region of the forest, it was determined that better environmental data was needed before analysis could take place.

Aside from the areas not analyzed for this study, the majority of soil units for the Fremont NF were still predicted and delineated for LTA units. The following sections provide an overview of the landscape features in the forest.

2.2 Landform

Much of the topography of the Fremont NF and its influence on other environmental features will be discussed in the LTA section of this study. However, a brief overview of the general landforms present in the forest will be given here. This will serve to familiarize the reader with a broad image of the landscape.

Most of the Fremont NF lies within the northwestern section of the Basin and Range Province (BRP), which is characterized by a transition from Basin and Range extension in northwestern Nevada to high volcanic plateaus in the northwesternmost area of Nevada, northeastern California, and southern Oregon (Lerch et al., 2007). The forest lies at some of the highest elevations in Oregon at approximately 4500-8600 feet, but its topography is dominated by gentle to moderately steep slopes, generally up to 40%. Only a small portion of the land contains slopes steeper than this range (Wenzel, 1979).

A few major block faults can be found throughout the forest. These fault scarps include Winter Rim, Abert Rim, and Coleman Rim. In contrast to much of the gentle and moderate topography of the forest, these areas are steep and unstable (Wenzel, 1979). As such, they are associated with thick, colluvial deposition.

Landscapes carved by major rivers in the forest also form steeper areas of topography. For example, the Sprague River begins its 90 mile stretch on Coleman Rim and Gearhart Mountain to the east (Perry, 1999). After passing over a series of marshes and low-lying hills, it joins another major river, the Williamson River. Collectively, these rivers contribute an average of 758,000 acre feet of water per year to nearby Upper Klamath Lake (Risley and Laenen, 1999).

Relief and landforms have a significant influence on a variety of ecosystems in the forest. Moreover, relief determines the locations of lakes, streams, and marshes, and influences soil formation and distribution (Carlson, 2001). Knowledge of the effect of landform is important for management practices in the forest.

2.3 Geology

In the original SRI, the surficial geology of the Fremont NF is divided into five main categories. These are pyroclastic and sedimentary rocks, basalt and tuff flows, fluvial deposits, rhyolites, and Mount Mazama ash and pumice deposits. To deduce how such a wide variety of lithologies were produced, a description of the geologic history of the area is necessary.

Within the BRP, the Fremont NF lies in a specific area known as the Klamath Basin, which as geographically defined, is the area drained by the Klamath River and its tributaries (Perry, 1999). The basin in its entirety covers part of south-central Oregon and northern California, an area nearly twice the size of Massachusetts. In Oregon alone, it covers approximately 5,600 square miles and almost all of Klamath County and smaller areas of Jackson and Lake Counties. Besides the BR, the Klamath Basin is bordered on its western edge by another geologic province, the Cascade Mountain Range.

The Cascade Mountains are geologically divisible into two separate regions, the Western Cascades and the High Cascades. The Western Cascades, at 20 to 33 million years old, are older than the High Cascades (Hammond, 1983 and Vance, 1984). These highly eroded mountains are comprised chiefly of Oligocene to Pliocene volcanic and volcaniclastic rocks (Wood and Kienle, 1990). In the Klamath Basin, the Western Cascades mostly consist of lava flows, andesitic mudflows, tuffaceous sedimentary rocks, and vent deposits. About 5 Ma, the Western Cascades were tilted upward, which created a sloping ramp on its west side and a steep drop on its east. This ramp casts the current rainshadow over the Klamath Basin, which keeps the climate drier and more semi-arid than the mountains on the western side of the Cascades (Knutson, 2006).

The younger, 5 to 7 Ma High Cascades are constructional and composed of rocks that are mostly Pliocene to recent in age (Gannet, 2007). These mountains are composed of prominent eruptive centers, which influence the forest environment. The most important of these centers is Mount Mazama (currently Crater Lake), as its eruption 7,800 years ago deposited tephra that greatly influenced the soils of the Fremont and Winema NFs. In the study area, most High Cascade rock deposits are relatively thin, measured only in hundreds of meters thick rather than the thousands measured elsewhere (Gannet, 2007). Volcanic vents and lava flows with minor interbedded volcaniclastic and sedimentary deposits dominate.

Like the Cascade Range, the BRP also contains geologically complex terrain, but much of its northwestern portion has not been well studied (Scarberry, 2007). However, despite being overlooked in past studies, this northwestern corner has recently become an area of research interest because of its complex tectonic setting that has been experiencing crustal extension over the past 30 million years. Deformation continues to this day, which is evident by the many Quaternary and Holocene faults throughout the region (Hammond, 2005).

The majority of the northwest margin of the BRP contains exposures of only the most recent volcanic units, because it is affected by a minor amount of surface faulting (Lerch et al, 2007). Most of these exposed volcanic rocks are younger than Middle Miocene Steens flood basalt, as magmatism has been focused towards the margins of the BRP relative to a more central location (Johnson et al., 1998). Volcanic rocks present in this region of the BRP are commonly interbedded with and locally overlain by late Miocene to Pliocene sedimentary rocks (Gannet, 2007). The types of sedimentary rocks present are numerous and include tuffaceous sandstone, ashy diatomite, mudstone, siltstone, and some conglomerates. These rocks are present both in horsts and grabens, which indicates that these deposits may partially represent an earlier generation of sediment-filled basins that have been subsequently faulted and uplifted.

There are, however, some volcanic rocks older than this age, but these are Paleogene units found in the Warner Mountain Range and the High Lava Plains (HLP) (Lerch, 2007). The HLP is a late Tertiary to Quaternary bimodal volcanic field underlain by widespread, thin lava flows of basalt interposed with rhyolitic ash-flow tuffs and tuffaceous sediments accented by rhyolite dome complexes (Jordan et al., 2007). It is an area of complex geologic activity, but because the boundaries of this study are located mostly east of this region, only a small amount of soil units on its eastern border are affected.

2.4 Soils

The soils of the Fremont NF are derived from a mixture of the geologic materials previously discussed, which are primarily volcanic parent materials, alluvium, loess residuum, and colluvium. The original SRI of the forest grouped soils into eight different categories based off of the combinations and variations of these main parent material types (Wenzel, 1979). While these classifications are useful as general guides to the soils in the Fremont NF, to understand the diversity of characteristics in them often requires supplemental information and observation of soils in the surrounding areas of the forest.

On a very broad level, soils in the forest and surrounding counties can be divided into two main categories, muck and mineral (Carlson, 2001). The more organic-rich muck soils are generally found in lowlands such as drained lakebeds and meadows, whereas the uplands of the Fremont NF are generally comprised of mineral soils ranging from sands to loams. Soils used for agriculture in the forest were generally formed in lacustrine or alluvial sediments weathered from tuff, basalt and diatomite. These soils tend to have lower bulk densities and higher water holding capacity than mineral soils formed in uplands or elsewhere (Carlson, 2001). This variety of soils demonstrates that like the geologic parent material from which they are derived, soils in the Fremont exhibit complex characteristics and can develop in a variety of environments.

Because the Fremont NF extends across two MLRAs, dominant soil taxa vary in each region. The dominant soil orders of MLRA 6 are Alfisols, Andisols, Inceptisols, and Mollisols (NRCS, 2006). Within these soil orders, certain soils stand out as characteristic of certain areas of the landscape. For example, the soil developed in the pumice and ash soils of the Mount Mazama eruption are primarily Vitricyrands, the most common of which is the Lapine Series. This soil is characteristic of the area in the pumice plateau of the Fremont NF. Minimally developed Haploxerepts are also commonly found in this MLRA 6, and are typically found in residuum, loess, and colluvium on mountain slopes from which they were derived. Although it is not listed as one of the major soil great groups of the MLRA, Xerorthents are abundant in this region of the Fremont NF as well. These soils are present in locations where thick mantles of ash overlie buried residual and colluvial soils.

In MLRA 21, the dominant soil order is Mollisols. However, small areas of Inceptisols and Histosols locally occur in basins. Like MLRA 6, MLRA 21 contains large extents of Xerorthents. These Xerorthents are in large part restricted to a transitional boundary between the two MLRAs and become more loamy, clayey and sandy going southward or eastward. In the lowland basins and meadows, the aforementioned mucky soils are present as Haplohemists or Humaquepts. The most commonly distributed and field-checked soils in MLRA 21, however, were a variety of

Argixerolls which were present on a variety of landforms including plateaus hills and mountains.

As previously alluded to, many other soils can be found throughout the Fremont NF. However, only the soils that were most prevalent and influential in the process of delineating LTA units for the forest environment have been discussed. At the small scale of this study, a more detailed description of the soils would not be resolvable.

2.5 Vegetation

The Fremont NF exhibits a wide range of plant communities, and the variety of environmental conditions gives rise to the biological diversity found in the forest (Hopkins, 1979). Similar to the pattern seen with soils, the type of vegetation observed in the study area depends on location. For example, on the western edge of the forest where deposits of pumice are present, plant community development and dynamics have been greatly modified in comparison to the rest of the forest. Traveling eastward away from this zone, topography generally becomes more varied and elevation increases, which influences the vegetation types found in these locations. This more varied topography consists of a pattern of associated coniferous stands, whereas the pumice plateau is generally dominated by a single species of lodgepole pine (*Pinus contorta*).

In grassland locations at the lowest elevations of the forest, Sandberg blue grass, big sagebrush, antelope bitterbrush, and Idaho fescue dominate (NRCS, 2006 and Hopkins, 1979). Meadows and basins are covered by sedges (*carex* spp.), wiregrass, and creeping wildrye. A large-scale effort has been made to restore and expand meadows in the forest by the removal of western juniper (*Juniperus occidentalis*), which is generally accepted to exceed its historic range of variation (Baker, 2004). Western juniper also encroaches on and infills areas known as the sagebrush steppe, where the main species are sagebrush, rabbitbrush, bitterbrush, and mountain mahogany. On many of the perimeters of the sagebrush steppe, western juniper has been removed by management and replaced by aspen, where they were once abundant.

Though a great variety of vegetation exists, the Fremont NF is primarily dominated by three main groups of conifer species (USFS, 1975). In the lower elevation ranges, western juniper is the most abundant. As elevation increases, the vegetation begins to grade into ponderosa pine (*Pinus ponderosa*), which becomes more prevalent. Finally, at elevations roughly above 5500 feet, vegetation becomes a combination of mixed conifers, which usually includes white fir (*Abies concolor*), incense-cedar (*Calocedrus decurrens*), and lodgepole pine (*Pinus contorta*) (Knutson, 2006).

Detailed descriptions of the vegetation patterns are described in the original SRI, which divides vegetation into eight main groups: 1. Meadow Zone 2. Grass-Shrub Zone 3.) Juniper-Shrub Zone 4.) Ponderosa Pine Zone 5.) Ponderosa Pine-Lodgepole Pine Zone 6.) Lodgepole Pine Zone 7.) Mixed Conifers Zone and 8.) Subalpine Conifer Zone. Whereas these groups are helpful as a general guide to forest vegetation, the 2006 Landfire vegetation layer (USGS, 2006) was used for prediction (Section 4).

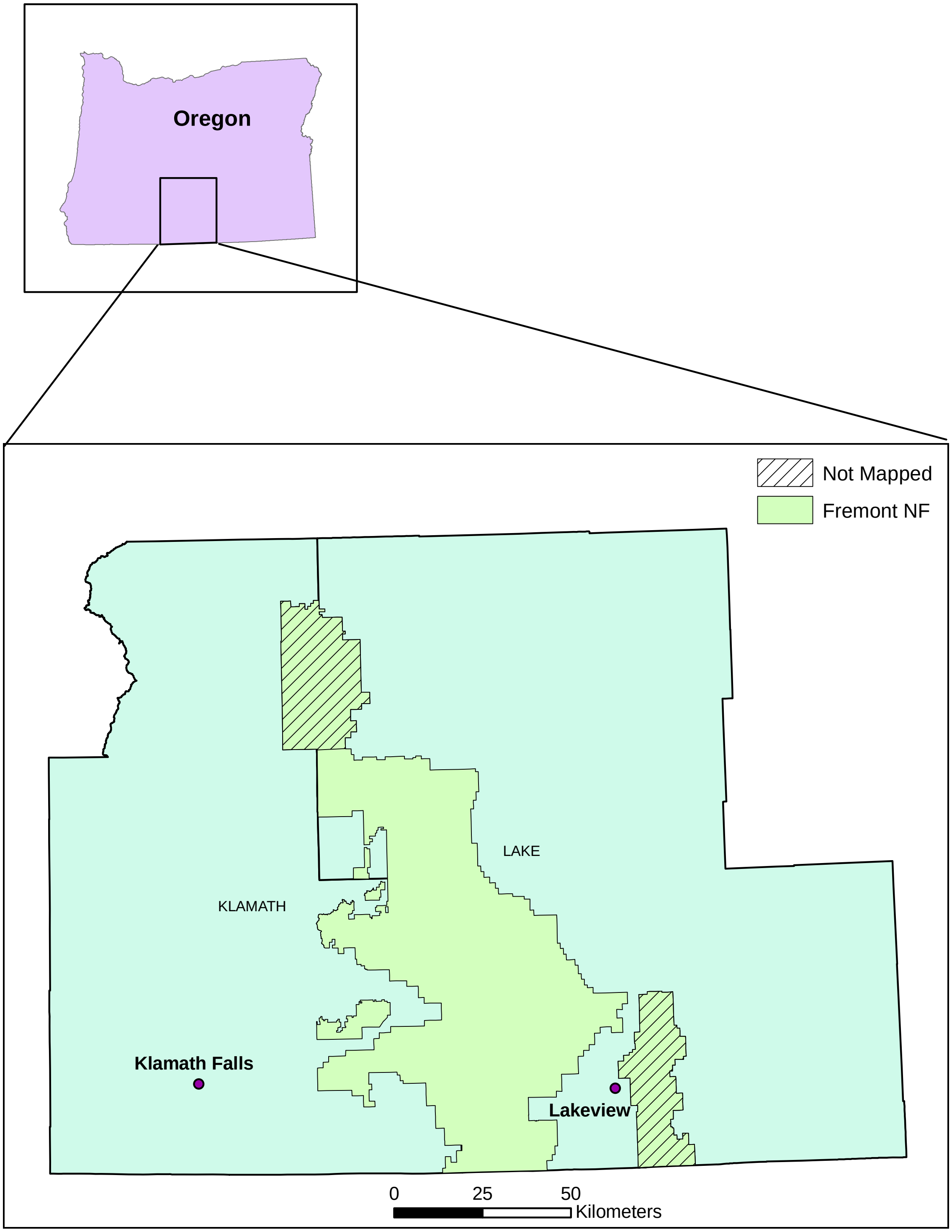

Figure 1- Study Area.

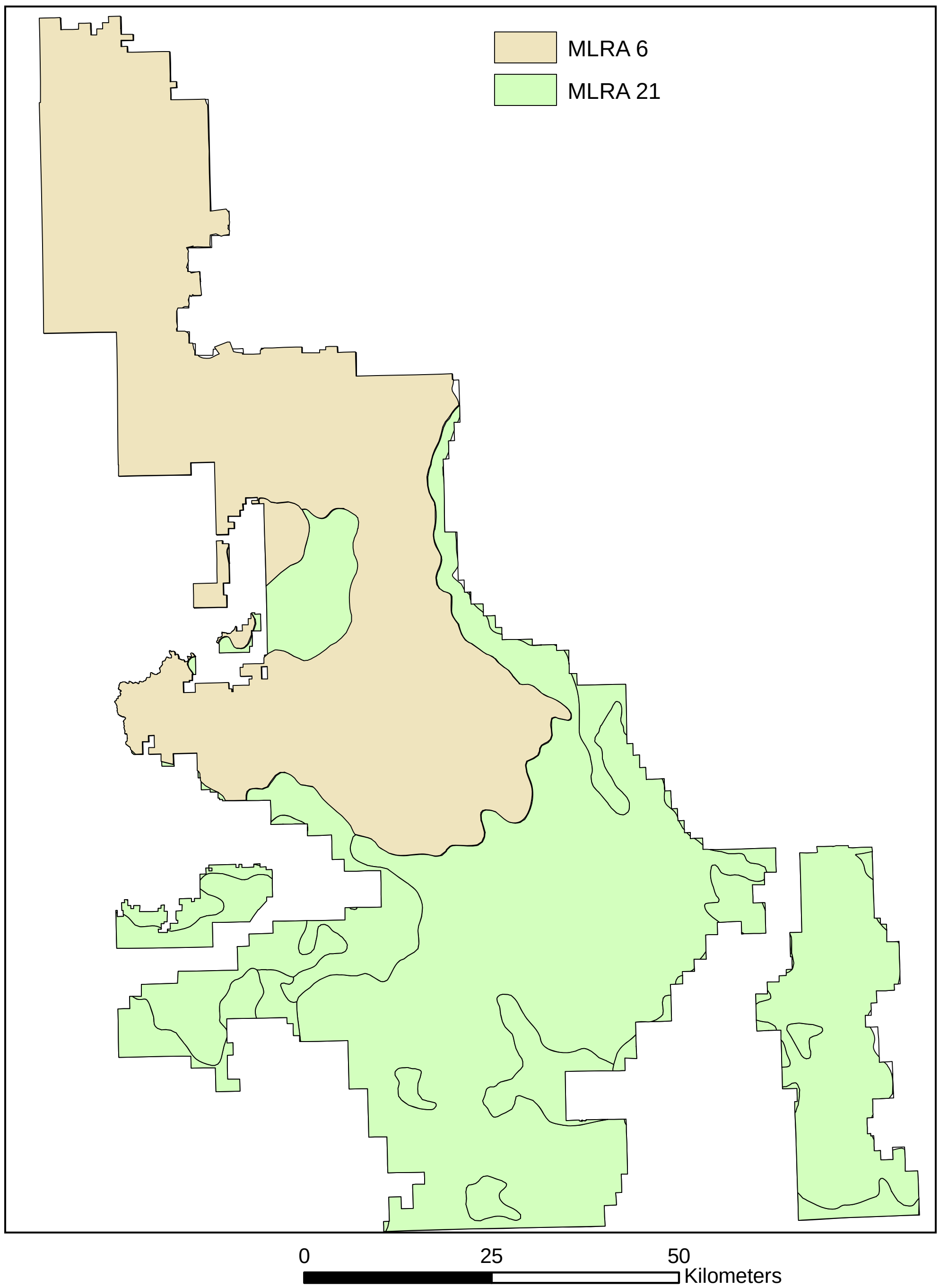

Figure 2- MLRA Boundaries in the Fremont National Forest.

LTA DELINEATION AND THEORY

3.1 National Hierarchical Framework of Ecological Units

On June 4, 1992 the USDA Forest Service assumed a policy of ecosystem management in order to better manage its national forests, grasslands, and research programs (McNab and Avers, 1994). The need for such a system and various attempts to devise one had been ongoing for decades. Many researchers such as Bailey (1983), Wertz and Arnold (1972), Omernik (1987) and Barnes et al. (1982) developed hierarchical ecological classification systems, which were intended to organize different ecosystems using a bioclimatic approach. Though no single system devised by one of these researchers was applicable from a global to local scale, the strengths of each system helped to create the structure for what is now known as the National Hierarchical Framework of Ecological Units (Table 1) (hereafter referred to as the National Hierarchy) (Cleland et al., 1997).

The National Hierarchy's main purpose is to use scientific rationale for the scaled categorization of ecosystems. This categorization consistently defined across all scales of management use, should improve efforts in national, regional and forest level planning, advance the understanding of the nature and distributions of ecosystems, and facilitate interagency data sharing and planning (Cleland et al., 1997). The National Hierarchy is divided into different ecological units in order to detect areas of land and water at various levels of resolution that have similar management capabilities and potentials. It was out of this classification system that the ecological unit used for this study, the Land Type Association, was chosen.

3.2 Prior Mapping Efforts

This study is not the first attempt to produce a map of the Fremont NF that is useful for land managers. As briefly mentioned in past sections, soil scientist David Wenzel (1979) produced a SRI of the Landtypes (LTs) of the forest. The objective of this inventory was to provide basic information about the soil, geology, vegetation, and landforms for the forest that would be useful to land managers attempting to implement multiple-use management practices. The implementation of multiple-use management was a response to Public Law 86-517, which in summary stated that national forests were to be managed in such a way as to produce high levels of renewable resources without impairment of the productivity of the land (Wenzel, 1979).

To delineate LTs, Wenzel used soil characteristics as his main guide. Using soils as the basis of LT units was based on the premise that soils are an essentially nonrenewable resource because of their slow development rate. As a limited resource that significantly contributes to its productivity yields, Wenzel used soil in conjunction with other landscape features to construct his classification system of the forest.

The current definition of an LT (Table 2) is similar to Wenzel's (1979), with the exception that the current definition also includes phases of soil subgroups, families or series. Delineations of the original Fremont NF LTs were made by photo interpretation, field observations, laboratory sampling and analysis, and research results that defined relationships. This work took place from April 1973 to October 1976 on approximately 1,452,000 acres of land.

When mapping was completed, the SRI was classified as a third order survey. Third order surveys are usually limited to use in planning for large areas such as rangeland, forest, recreational areas, and community planning (NRCS, 2007). The minimum size used for delineating map units was approximately forty acres. Additionally, the majority of large blocks of private land were excluded from the survey, although a few small parcels of private land were incorporated.

3.3 Current Mapping

The current study focuses on producing an LTA map of the Fremont NF. LTA units were first introduced by Wertz and Arnold (1972) in which they proposed a system of ecological units divided into a hierarchy of sections, subsections, LTA units and LTs. This hierarchy later evolved and was adapted into the National Hierarchy by Cleland et al. (1997).

To provide a more specific definition of the LTs and LTA units in the hierarchy, elements from the Ecoregion Classification System (ECS) were incorporated into the National Hierarchy. The ECS was developed by the Province of British Columbia in 1985. It uses the Terrestrial Ecosystem Mapping (TEM) methodology in order to combine the ecological features of physiography, surficial material, bedrock geology, soil, vegetation, and climate for the purpose of stratifying the landscape into organized map units (Province of British Columbia, 2006). This methodology forms the foundations for mapping ecological units at the land unit and landscape scales, with the latter being the scale at which the LTA is mapped. The methodology is based on State Factor Theory (Jenny, 1941, 1960).

Ecological units mapped at the landscape scale are based on biotic and abiotic features, which form the physical environment**.** Particularly important factors are landform, surficial geology, local climate, and morphometry, because these factors most directly influence soil and vegetation development (Jenny, 1960; Winthers et al., 2005). However, scientists in the soil and vegetation ecology disciplines have disagreed whether soil or vegetation is the more important factor for the basis of ecological units.

Both soils and vegetation are equally difficult to map, as different types cannot always be seen in aerial photography, satellite imagery, or digital elevation maps. As a result, each discipline has created its own classification of mapping. Soil science relies on soil classification and mapping in the perspective of the landscape, while vegetation ecology has traditionally considered multivariate methods in order to classify vegetation (Carleton, 1984; Yarranton, 1974). The amalgamation of both disciplines' views is what is used by those using the TEM method to establish ecological units. The TEM method is useful to many mappers delineating LTA units, because it establishes classifications when relationships between potential natural vegetation (PNV), soils, and other landscape elements are obscured by other ecological or biological phenomena**.** For this reason, the TEM approach is used to delineate LTA units in this study.

With soil and vegetation (or their surrogates) as the basic units for map delineation, LTA units are created using either the "top-down" approach or the "bottom-up" approach. The top-down approach delineates LTA units by dividing subsections into subdivisions. Abiotic factors are used as substitutes for soils and PNV. In contrast, the bottom-up approach forms LTA units by grouping together LTs based off of landscape features such as geologic rock types, soil complexes, stream types, lakes, wetlands, and vegetation communities (Cleland et al., 1997).

The bottom-up approach was used for this study. SRI LTs and ecological unit inventory (EUI) units of the neighboring Winema NF were grouped together to form the LTA units of the Fremont NF. These ecological units have major emphases on soil characteristics and PNV, respectively. LTA map units are defined by patterns in general landform, surficial and bedrock geology, soil subgroup and great group, and PNV. LTA map units are designed for display and use at a scale of 1:100,000.

Table 1- National Hierarchical Framework of Ecological Units.

Analysis Scale	**Map Scale**	**Ecological Units**	**Purpose, Objectives and General Use**
Ecoregions: Global Continental Regional	 1,000,000's to 10,000's of Square Miles	Domain Division Province	Broad applicability for modeling and sampling. Strategic planning and assessment. International planning.
Subregion	1,000's to 10's of Square Miles	Section Subsection	Strategic, multi-forest, statewide, and mulitagency analysis and assessment.
Landscape	1,000's to 100's Acres	Landtype Association	Forest or areawide planning, and watershed analysis.
Land unit	100's to less than 10 Acres	Landtype Landtype Phase	Project and management area planning and analysis.
Hierarchy can be expanded by user to smaller geographical areas and more detailed ecological units if needed		Very detailed project planning.	

**Table adapted from Cleland (1997) and Sasich (2006).*

Table 2- Comparison of Elements for Ecological Units at Landscape and Land Unit Scales.

Analysis Scale	Ecological Unit Levels	Geology	Geomorphology	Soil	PNV
Landscape	Landtype Association (LTA)	Primary lithology or groups of secondary	Geomorphic process and subprocess types	Great group and subgroup	Series and subseries
Land unit	Landtype (LT)	Secondary lithology	Landforms, element landforms, and morphometry	Subgroups, families, and series	Subseries and plant associations
	Landtype phase	Secondary lithology	Landforms, element landforms, and morphometry	Series and phases of series	Plant associations and plant association phases

**Table adapted from Winthers (2005).*

MATERIALS AND METHODS

4.1 Field Work

As the major foundation of the LTA units, it was important that the boundaries of the LTs of the Fremont NF were accurately mapped. Ground-truthing is required to determine map accuracy. Since the LTs of the original SRI were mapped with a major emphasis on soil characteristics, the most appropriate method was to collect field data of the forest soils. The approach taken to field-check the soils was similar to the process outlined in the National Soil Survey Handbook (NRCS, 2007) for fourth-order soil surveys. Areas of interest were first identified using the original SRI map and remotely sensed imagery. Then, representative areas were field-checked to determine soil patterns and composition of the map units. The areas of interest were selected on the basis of access to the greatest number of different SRI units, each of which covered a significant portion of the forest. In total, 48 individual SRI map units and 10 complexes were visited at 150 various locations throughout the forest (Figure 3). These units represent 994,820 acres of the 1.2 million forest acres, or 83% coverage.

Field-checks of randomly selected verification sites involved comparing the original SRI map, as well as its derivative to the site conditions and soil. On the western edge of the forest near the Winema NF, EUI maps were used for verification and compared to the SRI units as well. The use of both EUI and SRI unit maps during field-checks was performed to determine which ecological units better identified the soils in the forest, and will be discussed in the next section.

4.2 Data Preparation and Decision-Tree Analysis

Jenny's (1941) soil-forming factor model was used to as the basis to determine which environmental variables would be the most appropriate to use for soil map prediction. According to this model, soil is formed primarily under the influence of five main environmental factors expressed in the equation:

$$s = f(clorpt)$$

where soil, s, is a function of climate, organisms, topography, parent material, and time. Raster data layers covering the study area are selected to represent each of the CLORPT variables. The data layers are used to explore the spatial relationships between the dependent variable, soil, and the relevant independent environmental variables. Environmental variables used in this study are presented in Table 3.

All data layers were projected to UTM Zone 10, Datum NAD 83 and were subsequently clipped to cover both the area with the training data units and the area into which those units would be predicted. These layers were then converted to Imagine file format in order to be converted into a sampling grid by the Classification and Regression Tree (CART) sampling tool designed by Earth Satellite Corporation (2003). This sampling grid was then read by the program See5 to generate rulesets for decision-tree analysis.

Decision-tree analysis (DTA) is a means of producing rulesets, which then are used in a predictive model. As used in this study, DTA associates independent environmental variables with a certain dependent soil unit that has a direct or indirect relationship with those variables (Elnaggar, 2007). The DTA-derived soil-landscape model of the forest was used to produce the predictive soil maps. Predictive maps of the soils were generated using 10% of the training soil data and 5% of the samples for testing the predicted model. To improve accuracy, the boosting function in See5 was used in all predictions and was performed ten times for each map. Each time boosting occurred it developed a new sequence of decision trees, which improved the misclassification error in the previously generated trees. To ensure that insignificant variables were not affecting the accuracy of the DTA, the winnowing attributes function was used as well. This function is intended to remove any variables that do not significantly contribute to the formation of the dependent soil unit. In other studies conducted, using the winnow-by-attributes function typically removed the less significant variables (RuleQuest Research, 2007). However, in this study, winnowing was used more as a precautionary method, as no attributes were ever removed from any of the rulesets in generated for the maps.

The earliest predicted maps using only unmodified SRI soil units as training data had prediction accuracy levels ranging from the lower sixtieth to lower eightieth percentiles. To improve prediction accuracies, five major modifications to the training data were employed that increased levels to the lower ninetieth to upper ninetieth percentiles. The first modification that increased accuracy was the addition of EUI units as training data to correct for landform. Field checks revealed that the SRI description of the soil itself was correct for the majority of locations, whereas the landform on which the soil is present was often incorrect. In comparison, EUI units are accurate in identifying landforms as well as soil boundary, but the soil name for a given location was often incorrect. Though the EUI soil unit name was inaccurate, the consistent and accurate identification of landforms was significant, as geomorphology is the primary basis for LTA delineation. Prediction areas were organized into zones of similar soil type and the appropriate combination of EUI and SRI units were used for each zone (Figure 4). For reasons discussed in the "Study Area" section, only areas within zones 2-4 (areas mostly outside of the pumice plateau forest and areas west of the Warner Mountain Range) were predicted. Second, units designated as "Miscellaneous Mapping Units" in the original SRI map of the forest were removed because of their wide range in soil texture, slope, vegetation, and environmental factors that confused the DTA. In general, non specificity in training area data for these units leads to complex, error-prone and low confidence rules. Third, with the 60m grid cell side used for map predictions, some map units are not resolvable. Units less than 100 acres in size were removed. Fourth, many SRI map units were combined into complexes on the basis of landform. Some areas that were occupied by too many SRI units were aggregated into a singular SRI unit, as one individual SRI unit usually contained inclusions of many of the soils nearby. Fifth, after all other modifications to the training data were made, an Arcview extension majority filter tool was used to remove isolated, single pixels from the maps. The majority filter tool smoothes data by replacing cell values in the selected raster with the majority (most frequent) value of neighboring cells (Hooge, 2008). The amount that the majority filter tool increased accuracy varied by prediction and ranged from approximately 2-10%.

4.3 Statistical Evaluation

In order to evaluate the reliability of the predictive maps, a suite of classification and statistical analyses were employed. Classification analysis, required to group all of the soil map units into their respective classes, was the first step used in evaluating the maps. A parallelepiped classification analysis within the ENVI program (Jensen, 1996) was used to compare the modified ground-truth image of each Fremont NF zone to its matching predicted image. Parallelepiped classification uses a simple decision rule to classify multispectral data (Richards, 1999). Although the training and predicted maps themselves do not contain multispectral data, each layer is treated as if it were a spectral signature. In order to determine the dimensions of each parallelepiped classification in the image data, a standard-deviation threshold from the mean of each selected class was calculated by the classification. If a given pixel value (representing a soil class) is below the high threshold and above the low threshold for all of the bands being classified (in this case the two soil layers), it was assigned to that class. Areas remaining outside of any of the parallelepiped classes were designated as unclassified.

After the general parallelepiped classification was performed, both simple-descriptive and discrete-multivariate statistics (Jensen, 1996**)** were used to evaluate the modified ground-truth image and the predicted image of each zone. Overall accuracy, producer's accuracy, and user's accuracy all fall into the category of descriptive statistics. The overall accuracy is calculated by dividing the total number of correctly predicted pixels by the total number of pixels in the confusion matrix. Producer's accuracy is similar to overall accuracy, except that it is calculated by dividing the total number of correctly classified pixels for one class by all of the pixels that were predicted for that class. Producer's accuracy is a reflection of how accurate a class is in comparison to the same class in the ground-truth image. User accuracy is calculated by dividing the total number of correctly predicted pixels in a class by the total number of pixels in that class that were predicted in all classes. User accuracy reflects the programs ability to predict for a certain class using its algorithms.

The discrete multivariate method used to quantify the agreement between the modified ground-truth soil units and the predicted soil units was the kappa analysis (Cohen, 1960). The equation for the kappa coefficient *(K)*, as used by Elnaggar and Noller, 2008, is:

$$K=\frac{N\sum_{i=l}^{r} x_{ii} - \sum_{i=l}^{r}(x_{i+} * x_{+i})}{N^2 - \sum_{i=l}^{r}(x_{i+} * x_{+i})}$$

In this equation, N is equal to the total number of pixels in the confusion matrix, r is the number of rows in the matrix, x_{ii} are the diagonal entries of the error matrix, and x_{i+} and x_{+i} indicate the sum of row l and the sum of column l of the confusion matrix, respectively. The K value is representative of the agreement or accuracy between the ground-truth image used and the predicted image. This value varies from zero to one, where zero indicates no agreement and one indicates total agreement (Congalton, 1991).

4.4 Delineating Landtype Associations

Thirteen LTA map units are recognized in the study area, designed for display and use at a 1:100,000 scale. Using the bottom-up approach, similar groups of the modified SRI LTs of the forest were aggregated into LTA units. LTA polygon boundaries were drawn by digitizing the area around the selected LTs. After all LTA units were so delineated, they were named using the suggested TEUI method of a section and subsection name for the area in which the LTA occurs. In this way, all LTA units are named by their respective MLRA and subsection CRA. This name is followed by a two digit number from one to thirteen acting as a code for the LTA. For example, M6.11_01 identifies MLRA 6, Cascade Mountains, Eastern Slope and CRA 6.11 designates the Pumice Plateau Forest. Because the ‘6’ is used in both the MLRA name and the CRA name, it is only used once in the formal title. The number ‘01’ is the code for the first LTA unit delineated.

Accompanying attribute tables were constructed for each LTA map unit. Attribute data for LTA units are similar to those of the LT, except for the classification of the landscape elements, which are made at a more general level. All attribute tables include basic properties of the soil subgroup, PNV, geology, and landforms. Descriptions of the properties are listed in the “Results” section.

Table 3- Input Variables used for Predictive Mapping.

Variables	Data Source	Resolution (Scale)	Type of Data
Terrain Attributes- Elevation, Slope, Aspect	Derived from DEM (USGS-Eros Data Center, 1999)	10m	Continuous
Climate- Precipitation, Mean Annual Maximum Temperature, Mean Annual Minimum Temperature (1971-2000)	PRISM Group at Oregon State University (2006)	800m	Continuous
Geology	USGS (2003)	1:500,000	Discrete
Landfire Vegetation	USFS (2006)	30m	Discrete

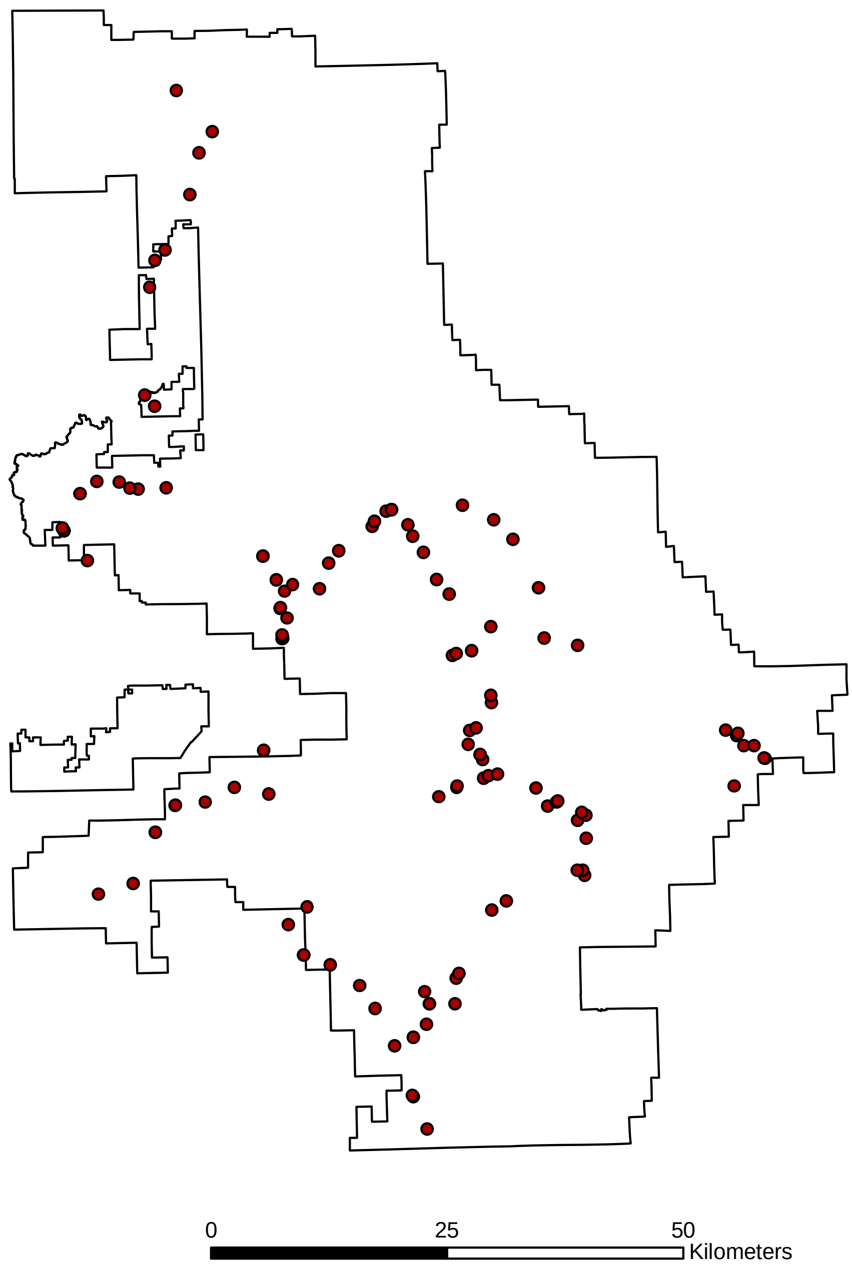

Figure 3- Field-check locations in the Fremont NF, Oregon.

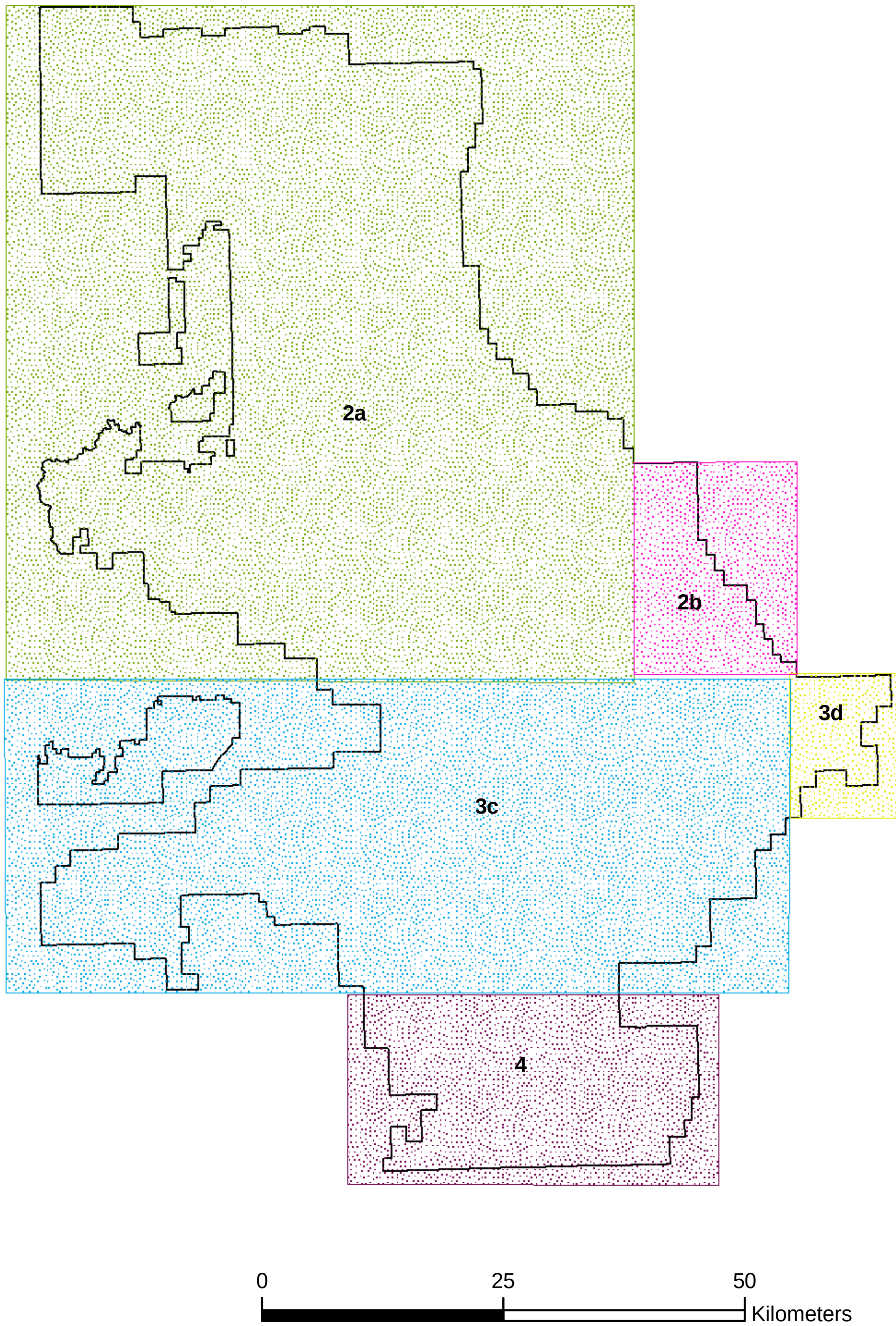

Figure 4- Fremont NF Prediction Zones.

RESULTS

5.1 Fremont Zone Prediction Accuracies

In total, five zones, 2a, 2b, 3c, 3d, and 4, were used to predict soil units in the study area. After all zones had been predicted and analyzed, they were merged into a single map. The decision to predict soil units in zones was based on several factors. First, not all of the soil units lie within the same MLRA. Though there are some areas where the boundary of a prediction zone overlaps into another MLRA, all of the prediction zones are comprised by the majority of one MLRA. Second, because of the variety of soil characteristics and other environmental variables throughout the forest, it was best to predict in more homogeneous sections. This helped to reduce the amount of confusion that could possibly enter into the DTA. Third, even if the previous two factors were ignored, the large size of the data layers alone made it infeasible to predict the whole study area at one time. Processing large datasets either resulted in an impractical processing time or a complete failure to generate the prediction model.

Overall, the breaking up of the forest into different zones was helpful, as it allowed for a more detailed analysis of smaller sections of the forest. The greatest consequence of predicting in smaller sections, however, was the amount of time it required. Each zone required the creation of new CLORPT layers along with all of the analyses outlined in the “Materials and Methods” chapter of this study. Though this process did prove difficult in some zones of the forest, the time required to perform these analyses was still substantially shorter than the time required to survey by traditional soil methods. Therefore, this time factor rendered the prediction of units by zone the most appropriate method for the scope of this study.

5.2 Zone 2

Fremont NF Zone 2 was predicted in two parts because it lies within two MLRAs. The majority of Zone 2a is within the boundaries of MLRA 6, with the exception of an area on its eastern border. In comparison, Zone 2b lies within MLRA 21. Zone 2 presented unique mapping challenges not present in other areas of the forest. Though the zone contains many of the loamy soils, scabrock flats, meadows, and vegetation common to the rest of the forest, it is also the area that is most influenced by Mt. Mazama pumiceous soils outside of the pumice plateau. Essentially, Zone 2 represents the interface between the residual and colluvial based soils of the central to southern Fremont and the pumiceous and ashy soils common to the pumice plateau.

5.2.1 Zone 2a

Zone 2a (Figure 5) had the lowest prediction accuracy in the forest when predicted with unmodified SRI units, at just 60%. In order to improve accuracy, Zone 2a was predicted using all of the adjacent Winema NF EUI units within MLRA 6, while all SRI units were removed. This prediction resulted in the map shown in Figure 6**.** The change in training data increased the accuracy to 91.3%, but this reflected the accuracy of the soils on landforms and not the accuracy of the soil that was actually present. In order to correct for soil name, the predicted map's attributes were manually changed and the correct SRI soil codes were put in place of the EUI codes.

There were only a few locations where EUI codes were deemed appropriate in the Fremont NF. For example, EUI codes 1018, 1023, 1031, 1058, 1059, and 1316 are labeled on the eastern slopes of Yamsay Mountain, located in the northwestern corner of Zone 2a (Figure 7). This location is within the boundaries of the pumice plateau forest, and it was reasonable to leave the EUI codes for pumice soils here. Although not a pumice unit, EUI code 1262 remains in this location as well, because it is a soil-creep unit commonly found mantling the slopes of mountains. Other soil-creep units, such as EUI units 1261 and 1266, also remain on the eastern boundary of Zone 2a. EUI unit 1266 occurs on sparsely vegetated, steep scarp slopes and is located in the landslide deposit units of the Fremont NF. Mantling the sides of 1266 and commonly found at the edges of other steep landforms is unit 1261.

The only other EUI codes that were not removed were units 1054 and 2027. Unit 2027 is described as a meadow unit, and because it was found in such a location with the correct vegetation types, it remained in its predicted area. Unit 1054 was sparsely found in the flats of SRI unit 84, accompanying scablands and areas influenced by fluvial processes. These landscape features are described in its unit description. The descriptions of the SRI units in these locations typically describe either the scabland feature or the fluvial process, but not both. Therefore, because EUI unit 1054 encompassed both processes, it was the best unit for these locations.

The majority of the units in the forest, however, were renamed with SRI units. This process mostly consisted of changing the EUI code to a SRI code for a given unit, but in some locations of Zone 2a more modification was required. Though the landforms predicted for the SRI soil boundaries were correct, separation of SRI units within some landform boundaries had to occur because various Fremont NF soils occur on the same landforms, as a result of various environmental factors.

For example, SRI unit 84, which covers most of the central and western portion of Zone 2a, initially was much larger. When using EUI units as training data, this SRI unit was predicted as EUI unit 1316 and covered its current space and an additional area to the north. After reviewing field data and what was mapped in the original SRI, it was determined that SRI unit 84 was the best match for its current location. The northern portion that was predicted as EUI unit 1316 was renamed mostly with SRI complex 350 and several other individual SRI units.

SRI unit 84 is an ashy soil that overlies buried basalt and tuff derived residual soils. It is also commonly found with SRI unit 85, a similar unit containing many of the same soil characteristics, and SRI unit 28, known as the “scabrock flats” unit. These three units were the most abundant within the area renamed as unit 84, and because unit 84 contains inclusions of both SRI units 28 and 85, it was deemed the most appropriate classification for the area. To the north, SRI complex 350, consisting of SRI units 35, 28, and 30A, was chosen because unit 35, a stony and residual soil, was more commonly found than 84 in this area. Additionally, 30A, similar to unit 28 but containing a deeper soil, occurs in greater abundance as well. Essentially, the area covered by SRI unit 84 consists of an ashy soil transitioning to scabrock flats, while SRI complex 350 is dominated by scabrock flats and residual soils with smaller areas of ashy soils.

Another area, originally mapped as EUI unit 1016 in the northern portion of Zone 2a, had to be divided into two SRI units as well. The area immediately surrounding the pumice EUI codes was renamed SRI unit 81. Unit 81 is bordered by SRI unit 85 along its northern boundary, while the units on its eastern side are residual and colluvial soils, many of which are unit 30A or contain inclusions of unit 30A. Unit 81 was chosen for this location because, like unit 84, it is an ashy soil that overlies buried and residual soils. Furthermore, it contains inclusions of both units 85 and 30A.

The area to the east of SRI unit 81 was renamed with many of the original SRI units. However, these SRI units were modified slightly to correct their soil boundaries. These SRI units include unit 64, another ashy soil unit with inclusions of units 30A, and 35, as well as 56A, another unit common to this area. Additionally, as a portion of this location is underlain by rhyolitic deposits, SRI units 40A, 41B, and 41C, residual and colluvial soils derived from rhyolite, are present here as well.

In areas where soil boundaries did not need to be redrawn, it was less complicated to rename units with their correct SRI code names. Examples of SRI units that required minimal boundary changes are units 89A, 77B, 88B, and complex 987. This is because these soil areas were mainly comprised of each of their respective units or units that were similar to themselves. Once all of the changes had been made to soil boundaries shown in Figure 6, it was rerun for an initial predicted map test to see how well the boundaries were defined. After this prediction, this test map was majority filtered to remove spare units and misplaced boundaries. This process produced the ground truth map and subsequently the final predicted map shown in Figure 5. Due to the improvements in

Zone 2a, which included correction of soil boundaries to follow landform and known soil boundaries, the prediction accuracy was increased. The final prediction accuracy of See 5 rulesets for Zone 2a was 96.3%.

5.2.2 Zone 2b

The challenges associated with mapping Zone 2b (Figure 8) were related to limitations in training data. Due to the absence of EUI training units that were suitable for this location, and because its soils and landforms are influenced by the HLP, Zone 2b had to be predicted using only its original SRI map units. The initial prediction using only unmodified SRI units yielded a prediction accuracy of approximately 78%.

To determine why the initial prediction accuracy was low, an investigation of the descriptions of the predicted soils was performed. While the soils predicted for Zone 2b seemed reasonable, as is common when using original SRI units as training data, far too many SRI units were predicted for the size of the zone and its landforms. This problem was somewhat difficult to remedy. While in other areas of the forest, the overly complicated units would normally be replaced with complexes, an inspection of this area revealed that the most reasonable complexes for the area had already been made. Therefore, the individual SRI units had to be left, as none of them were similar enough in description to group together into one unit.

The only methods by which the SRI units in Zone 2b could be simplified were to correct the boundaries of each unit and/or remove units. These modifications were accomplished by modifying unit boundaries, removing areas less than 100 acres in size, and using the majority filtering process to remove stray prediction units. After these initial improvements, the map was predicted again with 89% accuracy. Further improvements to the boundaries of the soils and another prediction yielded a final map that was 91.2% accurate overall. Though further manipulation of the training data was considered, in this location of the forest it is unlikely that a higher prediction accuracy would be realistic. Better environmental data and field-checks of soil boundaries in the location would be needed before further improvements could be confidently made.

5.3 Zone 3

Zone 3 was the most difficult location in the forest to predictively map. Though the initial test predictions of Zone 3 using unmodified SRI units yielded accuracy levels somewhat higher than initial predictions of Zone 2, many of the landforms and soils in the central Fremont are more complex than those found elsewhere. Topography ranges from flat meadows and lava plateaus to steep, highly dissected landforms in relatively short distances.

Zone 3 was another area predicted in two sections. However, the choice to divide the prediction of the zone into two sections was not based on MLRA boundaries, but on the limits of the training data used. Zone 3c used both EUI and SRI training units, while Zone 3d only used SRI training data. EUI training data was helpful for predicting soils on landforms in 3c, especially on the western edge of the forest close to the Winema NF. In Zone 3d, however, EUI training data could not be used because the characteristics of the soils become increasingly similar to the soils of HLP, and it could not be confidently ascertained if it was appropriate to use the EUI units for such predictions.

5.3.1 Zone 3c

Zone 3c (Figure 9) received many significant soil boundary changes and had the most SRI units aggregated into complexes in the entire forest. Its initial prediction using only unmodified SRI units yielded a prediction accuracy of 71.5%. To improve this accuracy level, a small amount of representative SRI units were combined with EUI units, which limited the types of landforms on which a given SRI unit could occur. Although EUI units were used to predict landform in Zone 3c, all EUI codes were removed and replaced with the correct SRI code. These replacements occurred because most of the EUI units, while correct in landform, were not similar enough to the SRI soils, and therefore were not the best match for each location. Also, some of the predicted EUI units were found to follow patterns in vegetation, with little regard to the soil that was present in a given location. The aforementioned reasons for changing EUI codes to SRI codes in Zone 3c can be seen in some examples below.

What was labeled as SRI unit 348 in the final predicted map of Zone 3c was originally mapped as EUI unit 1398. Two factors likely contributed to the identification of SRI unit 348 as EUI unit 1398. The first was landform, as EUI unit 1398 occurs on gently rolling and undulating lava plateaus, which would be predicted with many of the same variables that would predict the stony flats associated with 348. The second contributing factor is vegetation. Though the area in which 348 occurs does have an overall PNV of Ponderosa Pine and Juniper, because it is a complex, it is associated with a variety of vegetation types. In many of the sites where 348 was field-checked, particularly on the western boundary between the Fremont and the Winema where 1398 was predicted, the forest contained abundant white fir, which is its PNV. This mislabeling of the unit shows that when no other distinguishing features in the landform are present to differentiate between units, the next most significant variable will be chosen to distinguish between them. In this case, because the EUI units so strongly rely on PNV for map unit delineation, this is what the model chose to determine what soil would be predicted.

Another EUI unit that had to be changed was unit 1080, which was renamed with SRI complex 378. In each location where 1080 was predicted, unit 37A was the predominant original SRI unit in the area, accompanied by SRI units 30A and 28. The surface layers of SRI unit 37A consist of a dark brown to black loam or sandy loam, while EUI unit 1080 has similar surface layers of a very dark grayish brown ashy sandy loam. This sandy loam texture may be contributing to a particular PNV, which was detected in the training data and resulted in the mislabeling of the unit as 1080. However, there are multiple other reasons why unit 1080 is not predicted correctly in its predicted locations. Though the surface soils of 1080 and 37A are similar, 1080 is described as a dune or alluvial fan unit which is not present in these locations. Furthermore, unit 1080 is predicted in areas above its described elevation range. All of these factors render SRI unit 378 a more suitable prediction for the map unit.

Aside from units that had to be changed from EUI units to SRI units, there were several large areas in Zone 3c containing individual SRI units that needed to be made into complexes. For example, unit 37B was changed to complex 377, which is comprised of SRI units 37B, 67B and 68B. In the modifications made to the SRI training data, complex 377 was originally trimmed out and therefore could not be predicted. However, the choice to use the complex came after inspecting the landscape and the original SRI map and finding that the areas where 37B was predicted in test maps coincided with locations that contained both 37B and 377. Additionally, a large section of what was predicted as 37B in test maps also contained complex 648 in the original SRI. SRI complex 648 is completely comprised of SRI units 67B and 68B, which are two of the components of 377.

Another individual SRI unit that was predicted in test maps and changed into a complex was unit 77A, which was renamed with complex 417. SRI complex 417 is 50% of 41B and 50% of 77B. Determining why the part of the complex that should have been predicted as 77B rather than 77A remains elusive, especially because unit 77B was available as a training unit used for prediction. Regardless, because 77A was predicted on slope ranges of 16-40%, 77B was deemed the more appropriate unit for the complex. In field-checks, 41B was also found in the areas where 417 was named, along with other units derived from rhyolitic residual and colluvial soils such as 41A and 42, both of which are inclusions in 41B.

The last individual SRI unit to be changed to a complex was unit 30A to complex 376. The mislabeling of 30A as 376 is another instance where the PNV by which the EUI units were delineated determined how the soil units were classified. Both 30A and 376 occur on the same large expanses of what is labeled as Northern Rocky Mountain Ponderosa Pine Woodland and Savanna in the vegetation layer. Even though the landforms on which they occur are significantly different, the type of vegetation with which they were associated was consistent enough to cause a misclassification in this zone. Determining where to label 30A with 376 was fairly simple, but the changes made to these units did have an effect on the error map of this zone, which is discussed later in this study.

After all changes to EUI units and SRI complexes were made, the final prediction accuracy for Zone 3c was 95.1%. This represents an increase in accuracy of over 23.6%, second only to the accuracy increase of Zone 2a. The use of EUI training data significantly helped to deduce landform in this zone, and the substantial improvement in accuracy is reflective of how much the soil boundaries on these landforms needed to be changed.

5.3.2 Zone 3d

Zone 3d (Figure 10) contained some of the most homogeneous soil units in the forest. The majority of the predicted soil in the area is either exclusively SRI unit 37B or a complex which contains unit 37B. Due to the fact that the majority of this predicted area was classified with one unit or a similar unit, it had one of the higher initial prediction accuracies using unmodified training data, at 82%.

The challenges associated with predicting this zone were due to the limitations of training data outside of the original SRI. Much like Zone 2b, EUI units were not appropriate to use as training data because the zone's proximity to the HLP rendered many of its soil characteristics significantly different from the Winema NF EUI soil units. However, because this area had one of the highest initial predictions and because the original map units were mapped well on its landforms, it also required the smallest amount of correction. As with all other areas predicted previously, any units covering less than 100 acres in size were removed and the majority filter was performed on the initial prediction image to remove stray units that had been predicted in unsuitable areas. The final overall prediction accuracy for Zone 3d was 90.7%. Though this zone has the lowest prediction accuracy of all the zones predicted, it has the potential to be predicted with higher accuracy if the training data is improved by future field-checks and more environmental data.

5.4 Zone 4

Though Zone 4 (Figure 11) could not be mapped using EUI units, as there were no adjacent units present, the initial prediction accuracy of Zone 4 was 83%, the highest of all initial prediction accuracies using unmodified SRI units. The original SRI units of Zone 4 followed landforms accurately and used the least amount of overly complicated SRI units for one area out of the entire forest. Complexes were abundant and already covered much of the area. In all cases they only needed to be expanded into some bordering locations where units that comprised the complexes were located.

For example, the most significant changes to Zone 4 involved the expansion of complexes 348 and 378 into adjoining units. In the western portion of the zone, SRI complex 348 was expanded into the surrounding units composed of 34A, 28, and 30A, its three components. The same adjustment was made to the eastern portion of Zone 4 with SRI unit 378, where it was expanded into the surrounding units 37A, 30A and 28, also its components.

Complexes such as 376, 675, and 503 follow their described landforms well and did not need to be altered. The only other changes made to Zone 4 were to remove areas smaller than 100 acres in size before a test prediction was made. This test prediction yielded a prediction accuracy of 91%, and after performing a majority filter to the map and smoothing boundaries once more, the final predicted map had a prediction accuracy of 92.8%.

Though this final prediction accuracy increased by almost ten percent, updated improvements in the geology layer for this area would most likely improve its accuracy. While the geology of the Fremont is complex in general, it becomes even more so in its southern and most eastern extents. Substantial improvements to this layer were beyond the scope of this study, but would be recommended before future predictions were performed.

5.5 The Final Predicted Map

Figure 12 shows a map of all of the Fremont NF zones merged together. Due to the necessity to predict the Fremont NF in sections, both because of landform characteristics and the limitations of the software program, some soil units had to be modified where boundaries between zones met. These changes were all relatively minor, but for any future field-checks it is recommended that individual prediction zones be used in cases of uncertainty.

A comparison of the original SRI map of the Fremont NF to the newly created map reveals significant changes, which are largely the result of changes to soil boundaries on landform and an overall reduction in SRI units in the forest. The improvement in soil boundaries on landform was chiefly due to the addition of EUI units as training data. Though most of these EUI unit names were removed from the final map, their use in initial predictions guided the SRI units onto the correct landforms. Inspections of the SRI map unit attribute tables and field-checks of the SRI units revealed that many SRI units in the original map are mapped on incorrect landforms. The use of EUI units as training data helped to reduce this occurrence, and the SRI map units in the final predicted map more consistently follow the landscape features described in their attribute information.

Reductions in SRI units in the forest occurred for several main reasons. The first, and most consequential reason, was that many individual SRI units were aggregated into border complexes which include them. The decision to aggregate individual SRI units into neighboring complexes was based on field observation and prediction results. Field-checks in locations where this mixture of SRI units and complexes were present revealed that soil characteristics did not significantly differ from one map unit to another, and in many cases not at all. This observation was further supported by prediction maps of these locations. During initial predictions, considerable DTA confusion was the result of an inability to correctly predict areas where similar SRI units and complexes occurred in close proximity. This problem occurred because the complexes and their inclusive SRI units were predicted with many of the same environmental variables, but were labeled differently in the training data. Because units sharing the same environmental predictors were labeled differently, the DTA was not able to confidently predict boundaries between them. This confusion resulted in a lower prediction accuracy.

To correct for this issue, two tests were employed. The first test involved predicting without complexes in the training data and the second involved predicting with SRI units aggregated into complexes. When all complexes were removed from the map training data, prediction accuracy decreased. Conversely, when SRI units were aggregated into neighboring complexes in the training data, prediction accuracy increased, in some cases by as much as ten percent. Due to the results of these prediction tests, it was determined that predicted maps of the forest were more accurate when neighboring SRI units were aggregated into complexes and were included in the training data.

Another reason that SRI units were reduced in number was because some units were removed from the training data of initial maps. This removal primarily occurred by two measures. First, units that were confusing the prediction model, like the original SRI "Miscellaneous" map units, were removed manually from the training data. Second, during the process of running initial test predictions, units that covered small acreage sizes (usually less than several hundred acres), were generally filtered out by the DTA. The removal of these units by prediction did increase accuracy, but not without consequence, because some of the small units that were removed were the best matches for their respective locations. This need to sacrifice some of the smaller units from the map is another instance where the 60m grid cell size of the map determines how much detail can be resolved. If a smaller grid cell size is ever used in future prediction of the study area, some of the smaller detailed units may remain.

The final reason that SRI units were reduced was due to the aggregation of multiple SRI units into an individual representative SRI map unit. However, this reduction method was only used for a very small number of units in MLRA 6. These units are 81, 89A, 84, and 87. The reasons for aggregating multiple SRI units into one representative unit are similar to the reasons for aggregating SRI units into complexes. These specific units were chosen to extend over inclusion units because field-checks of these soils did not reveal satisfactory differences between the originally mapped units. For example, though much of the region classified as unit 84 also was originally mapped alongside of unit 85, field-checks of these locations did not reveal any of the differences between these units that were described in the SRI. This phenomenon occurred with the other units used as representative units as well.

For clarification this observation is not to suggest that there is no basis for the unique map units described in the SRI. Rather, the assertion here is that in the locations checked, features which distinguished one unit from another were not present in the landscape. For this reason, it is proposed that the few individual SRI units which replace their inclusions be viewed in the same way as a complex.

Understandably, there are concerns that arise when using this method. One of the most relevant concerns is that, as seen in other studies, larger map units are predicted with higher accuracy than smaller units (Friedl and Brodley, 1997; and Elnaggar and Noller, 2008). Therefore, it would appear that aggregating units into one large unit does not accurately reflect the soils in the field, but rather the ability of the program to more accurately predict large units. This is a valid concern, but the choice to aggregate multiple SRI units into one individual unit is primarily based on field observation. Undoubtedly, there are many units in the forest where using an individual SRI unit as a representative for others would not be appropriate, such as units associated with meadows, or other distinctive landscape characteristics. However, the choice to use units 81, 89A, 84, and 87 as representative units was based on experience with the patterns of these particular units. Moreover, these units all occur in MLRA 6. As described previously, the soils and landforms in MLRA 6 are more homogenous and less complex than those of MLRA 21. Therefore, soils in MLRA 6, especially in the western extents of the forest, are likely to share more of the same soil characteristics than different.

When comparing the final predicted map to the original SRI map of the Fremont NF, it is clear that soil boundaries have been significantly altered. These changes are not without cause, as observation in the study area and prediction of the soil map units demonstrated a need for boundary correction. All zones predicted experienced substantial improvement in accuracy, and modifications to the training data were responsible for this improvement. Changes to map units in the Fremont NF map rendered a final map which more clearly demonstrates soil patterns on the landscape than the original SRI map. Therefore, this final map was found to be more suitable for the purpose of delineating LTA map units in the forest.

5.6 Zonal Statistics

Upon the completion of predicting soil units, a confusion matrix and error map of each zone was made. This next step in the analysis was helpful, because it confirmed many of the suspected strengths and weaknesses of the prediction model. Areas that were predicted well had little misclassification associated with them, while areas not predicted well, due to the topography, vegetation, or other environmental variables, had more misclassification. The statistical analysis verified that the observations made in the field and lab were having a significant effect on how accurately each zone was predicted.

A summary of the statistics of each zone is shown in Table 4. While all zones were predicted with high kappa coefficients and overall accuracies, a detailed inspection of the confusion matrix and error map of each zone revealed that there were several common patterns affecting the accuracy of all prediction zones by varying degrees. These patterns were analyzed in order to determine their significance in relation to the mapping process.

One pattern that affected all of the zones significantly was the result of the changes in shape or reduction in size of certain soil units during the prediction process. For example in Zone 2a (Figure 13), complex 892 and unit 76B (Figure 14) had producer's accuracies of 59.1 and 60.3%, respectively, and showed higher concentrations of misclassification around their soil boundary units. Misclassification around these units was occurring because of their change in shape and reduction of size from the ground truth image to the predicted image. In the ground truth image, unit 892 was approximately 820 acres in size and unit 76B covered 210 acres. In the predicted image, however, these units decreased substantially and covered 770 and 130 acres, respectively. To the north near the pumice plateau units, changes in unit shape were resulting in higher levels of misclassification as well. This area is where many of the small SRI unit replaced unsuitable EUI units. Although these units did not experience significant reduction in size like units 892 and 76B, their shape on the landscape was altered from the ground truth image to the predicted image. Additionally, because smaller units were generally not predicted as well as larger units, misclassification around these units was likely to occur.

While it may seem of concern that this transformation in unit shape is a widespread phenomenon throughout the forest, it is important to note that the most significant changes in shape or reduction of size generally occurred with the smallest and scarcest units in each zone. Therefore, the observation that smaller and more obscure units are associated with more misclassification may be more informative than problematic. This recurring pattern reveals that these units may need to be modified or eliminated from future maps of the study area at this scale.

Misclassification due to an abundance of small units occurs most frequently in Zone 2b (Figure 15). This zone is also where the unit with the lowest producer's accuracy in the forest, unit 61 occurs. Like units 76B and 892, unit 61 was reduced in size from its ground truth image to its predicted image from 350 acres to only 117 acres. Such a substantial change in size was likely to render a low producer's accuracy and reflect on discrepancies between the ground truth unit and the predicted unit. The problem with the abundance of small units is exacerbated even more by the fact that many of these small units are on varied terrain, and exact boundaries between all of the complicated units is difficult to predict. This problem is visible along the boundaries of units that occur on flat slopes, like complex 503, which borders many steeper units, such as 57 and 60.

Zone 2b is one of the predicted areas where further field-checking is recommended before future predictions were made. The overall concentration of misclassification around boundaries and the fact that the unit with the lowest producer's accuracy occurs here seems to support that a future map of this area would benefit from more field-collection and environmental data. Furthermore, though they do not experience as much misclassification as Zone 2b, Zones 3d and 4 would benefit from more field-collection and the addition of environmental variables as well.

Though not changed in shape or reduced in size, another unit that was significantly modified and was associated with higher misclassification was unit 30A in Zone 3c. As the reader will recall, many of the units assigned as 30A in test predictions had to be changed to 376 in Zone 3c, because they were found to be following vegetation patterns rather than landform. However, there were some areas where 30A was a better match than 376 because of flatter terrain. The final predicted image detected these flatter areas and mapped unit 30A in these locations. An example of an area where 376 was changed to 30A can be seen in Figure 16. The entire unit is manifested as a large misclassification area between the two maps, even though unit 30A is more suitable for this location. Though the discrepancy between 30A and 376 was noticed early in the prediction process, the misclassification mapping of this unit and other units is useful, because it directs attention to areas where more inspection may be needed to assess how accurately the prediction model is working. This helps with the process of modifying or eliminating units before final classifications are made.

As briefly mentioned along with other patterns affecting misclassification, patterns in landform also significantly impacted each zone. Some of the most apparent concentrations of misclassification associated with landform occurred in Zone 2a in the area that covers Gearhart Mountain and throughout Zone 3d (Figure 17), because of its overall steep terrain. Gearhart Mountain is one of the highest points in the Fremont NF at 8,364 feet above sea level, second only to Crane Mountain in the Warner Mountain Range at 8,454 feet. The mountain is characterized by steep slopes and environmental features change within short distances. Though this area was mapped with only a few soil units that share many of the same environmental conditions, deciding exactly where the boundaries of these units occurs is challenging, as the factors that would indicate their boundary delineations are not always retrieved by the prediction model. It was difficult to determine boundaries in Zone 3d as well, because most of its terrain is comprised of steep slopes from 16-40%, where many small soil units occur. In locations like these, it is very difficult for the prediction model to provide definitive boundaries because the environmental features and landforms they occur on are all very similar.

Though there were several patterns that could be identified which resulted in misclassification error, these were insignificant and the prediction maps are thus useful. All maps were predicted with high kappa coefficients and overall accuracy, and error maps of each zone revealed that the majority of space in each zone was classified correctly. Furthermore, all problems that resulted in misclassification were consistent with what was observed in the field and in the lab. These misclassifications revealed more about the strengths and weaknesses of each mapped zone, and will be useful for future analysis of the study area. Therefore, the results of the prediction analyses confirm the first hypothesis, as a more accurate map of the Fremont NF soils has been achieved through the use of PSM.

5.7 Landtype Associations

5.7.1 Explanation of LTA tables

The LTA map of the study area is shown in Figure 18. LTA boundaries were informed by similar groups of SRI units and landform boundaries, which were identified with a hillshade layer of the study area. These variables are described in extensive detail in Tables 5 and 6. A description of other important landscape features found within each LTA unit is shown in Table 7**.** Major emphasis was put on soil, geology, landform, and PNV, much like in the original LT, but at a broader scale. As soils and landform were the most important variables in determining LTA boundaries, Tables 5 and 6 are discussed below.

Table 5 will be discussed briefly because soils and their interaction with the environment has been thoroughly discussed in this study. However, some of the columns describing various soil characteristics need further elaboration in order to be used correctly. In the table, soil subgroups and great groups were chosen to represent major soil properties for each LTA map unit. While other soils with similar characteristics or of a smaller extent do occur in each LTA unit, the soils shown act as representatives for the entire unit. Each LTA unit's surface and regolith features are described as well. In this study, "surface" refers to the texture of the "A" horizon, while the regolith refers to the unconsolidated material below the "A" horizon and above the bedrock. All five soil textural classes shown in Table 4 are derived from the USDA Soil Survey Manual (USDA, 1993). The last column in the table indicates the parent material from which each soil was derived. Here, parent material indicates the type of surficial deposits which influence regolith properties.

Whereas many of the column headings of landform Table 6 are more self-explanatory than Table 5, the various landforms described require further explanation. One of the most common landform categories found in the Fremont NF LTA map units is plateaus and tablelands. This group of landforms occurs on relatively flat, 0-15% slopes, and usually consists of multiple layers of basalt lava flows. Depending on location, the plateau and tableland landforms have a variety of vegetation types and other smaller types of landforms associated with them, which separate them from other LTA map units. For example, M6.11_04 and M6.11_05 are very similar in landform overall, but M6.11_04 is associated with small eruptive centers like Shake Butte and Green Mountain. In contrast, M6.11_05 is associated with large valleys that surround the abundant streams that run through it. Differences of a more remarkable nature can be seen between between plateau and tableland landform units as well, as demonstrated in LTA map units M6.11_02 and M21.2_09. The landscape of M6.11_02 is covered with distinctive, thick and ashy soils as a result of the neighboring pumice plateau. These features stand in sharp contrast to M21.2_09, which is filled with thin, residual soils associated with scablands.

In contrast to the plateau and tableland LTA units, steeper LTA units, such as M21.2_07, 08, and 11 and M6.11_06 and M6.11_13, can all be generally grouped as units formed by uplift and subsequent stream erosion. This erosion is manifested in the steeply dissected ridges and slopes of the mountains in many of these LTA map units. Slope gradients in these LTA units can be as high as 50%, and all geologic types can be found on these landforms, which helps to differentiate between them. For example, M21.2_07 occurs mainly on rhyolitic domes, while M21.2_08 and M21.2_11 consist of domes, ridges, and mountain sideslopes associated with pyroclastic and sedimentary rocks. LTA units M21.2_08 and M21.2_11 are especially similar to one another, and are separated because of small differences in their soil characteristics and PNV.

Besides flat and steep LTA units with characteristics that are common throughout the forest, there are other LTA units which contain landscape features or landforms that are significantly different. One such unit is M6.11_01, which occurs on slopes from 0-15% much like the plateau and tablelands landforms. However, because it is located in the pumice plateau, its soils are much different from soils in the rest of the forest, and it is the only LTA unit listed with a PNV of white fir. LTA unit M21.2_12 is dissimilar from its neighbors as well, because it occurs on landslide deposits. The series of benches intermixed with hummocky, irregular mounds and depressions distinguishes this unit’s landforms from all those around it.

Many mixtures of the soil and landform features described in each LTA unit table can be found in the forest, but those described are meant to serve as representatives for each region delineated. The following section elaborates more on the reasons for each LTA unit delineation. Furthermore, general patterns in the landscape and soils in each LTA unit are discussed as well.

5.7.2 General LTA Soil and Landscape Patterns

Distinct differences can be seen between the LTA units of MLRA 6 and MLRA 21. Several LTA units in MLRA 6 follow SRI unit boundaries very closely, such as M6.11_02, M6.11_04, and M6.11_05, representing SRI units 81, 89A, and 84, respectively. These LTA units follow soil boundaries closely because SRI units within MLRA 6 generally occur on less complicated landforms than those in MLRA 21. Furthermore, environmental factors do not change drastically within many of the large areas drawn. In comparison, SRI units in MLRA 21 occur on more varied terrain where environmental features change within short distances. Identifying changes in the landform was crucial to making the best decision for a LTA unit boundary in MLRA 21.

Differences within each MLRA's LTA boundaries can be deduced as well. Though much of MLRA 6 is comprised of LTA units on 0-15% slopes, distinctions between soil characteristics and surface features in the landscape led to the separation of these map units. In the northern region of MLRA 6, differences between LTA units are primarily driven by changes in soils characteristics. This is especially true in the pumice plateau forest, where soils M6.11_01 are considerably different from soils in the rest of the study area. Nearby, although containing traces of the Mazama pumice present in M6.11_01, M6.11_02 becomes noticeably different from its neighboring LTA. Here the ashy, but not nearly as pumiceous soils of SRI unit 81 become dominant and overlie buried residual soils. Stony patches of SRI unit 30A (an inclusion of 81) are also mixed in with 81.

Going eastward from LTA M6.11_02 into M6.11_03, the soils become less ashy, are derived from more residual and colluvial sources, and units such as 30A become more prevalent. However, SRI unit 64, a gravelly and residual soil mixed with some ash does occur here as well, because it is partially derived from rhyolitic ash-flow tuff. Nearby are other SRI units influenced by rhyolitic tuff flows such as 40A, 42, and 41C, all of which are residual and colluvial soils derived from rhyolite. Most of M6.11_03, however, is comprised of residual and colluvial soil derived from basalt or andesite, such as units 30A, 28 or 35. SRI complex 350 comprises most of M6.11_03 and is composed of the three previously mentioned units.

In the flatter central to southern portion of MLRA 6 occurring on 0–15% slopes, the landscape is covered largely by ashy soils overlying old residual soils derived from basalt, andesite and tuff. The thickness of the ash in these locations is variable and can be up to six feet deep (Wenzel, 1979). The two main LTA units of this region, M6.11_04 and M6.11_05 are separated not on distinct soil characteristics, but on landscape features discussed in the previous section, as well as on elevation range and PNV. M6.11_05 occurs on a lower elevation range than M6.11_04 at 4500 to 5800 feet and its PNV is Ponderosa Pine. M6.11_04 occurs at an elevation range between 5800 to 7800 feet and its PNV is Lodgepole Pine.

Two of the three LTA units composed of SRI units on steeper terrain in MLRA 6 have soil characteristics similar to the flatter LTA units containing ashy soils overlying buried residual soils. The other dissimilar LTA occurring on steep landforms in MLRA 6, M21.2_07, occurs in both MLRA 6 and MLRA 21. Though the LTA occurs in both

MLRAs, it is named after MLRA 21, because it covers a larger area within its boundaries. M21.2_07 occurs on distinctive rhyolite domes, hence its formal name. Like many of the other LTA units, the soil in M21.2_07 is a mixture of ashy and residual soils. However, the distinct landform that it occurs on and the fact that its soils are mostly derived from rhyolites, tuffs, and breccia differentiate its soils from the ashy soils found elsewhere in the forest.

In contrast, the two steeper LTA units in MLRA 6 that are similar to the flatter LTA units of MLRA 6 are M6.11_06 and M6.11_13. M6.11_06 is composed entirely of SRI unit 87, a soil unit that occurs on slopes in transition zone locations. M6.11_06, or SRI unit 87, contains a mixture of the soils of its neighboring LTA units, but has a higher slope range than its neighbors. It also occurs in a transition location south of M6.11_13, where many of the inclusions of SRI unit 87 occur on colluvial slopes as well. M6.11_13, is mainly composed of SRI units 88B and 89B, soils that are very similar to the soils of LTA M6.11_04. Unlike M6.11_04, however, M6.11_13 occurs on steep slopes from 16-40% and also differs in PNV, which is mixed conifer. M6.11_13 stands out as one of the most distinct LTA units in the study area, as it is mostly comprised of the steep and dissected topography of its underlying structure, Gearhart Mountain.

Most of the LTA units of MLRA 21 vary greatly in landform from the LTA units of MLRA 6. However, the exception to this observation is LTA M21.2_10. This LTA rests on topography similar to many of the flatter LTA units found in MLRA 6 and appropriately contains soils common to both MLRA regions. Both ashy and residual soils along with small patches of scabrock flats can be found in this LTA unit.

Appropriately, much of it is located in the transition boundary between MLRA 6 and MLRA 21.

In most cases, however, the LTA units of MLRA 21 have more remarkable changes between them and very recognizable landscape features. For example, M21.2_12 which occurs on landslide deposits beyond the eastern border of MLRA 6, differs greatly from the flat and stony terrain of M21.2_09. M21.2_12 is characterized by steep landslide and debris-flow deposits with sparse vegetation in its northern portion and shrubs and mixed conifers becoming more abundant in its southern extent. This unit contains several soil-creep units and represents some of the most complex terrain found in the forest. In comparison, M21.2_09 consists of a large area of soil units and complexes found commonly throughout the forest. Scabrock unit 28 and its accompanying similar unit, 30A, are abundant here. These units are often joined by 34A, the three of which combined form complex 348. The terrain overall is full of stony and gravelly residual soils, most of which are scablands. Very little of this terrain is over 15% slope and is mostly dominated by Ponderosa Pine and Juniper, commonly found throughout the forest.

The last LTA map units to be described, units M21.2_08 and M21.2_11, rest on very similar landforms, as they both occur on steep topography associated with eruptive centers. Nonetheless, their PNV and slope range is different. M21.2_08 has a PNV of juniper and ponderosa pine, while M21.2_11 has a PNV of mixed conifer. Furthermore, their slope ranges differ and the general topography of M21.2_08 is somewhat gentler than M21.2_11.

The observation that there are many similarities intermixed with slight differences between soil units and LTA units, like those previously discussed, is common throughout the Fremont NF. Though many soil characteristics, vegetation patterns, and landforms are similar in the forest, the variety of ways that these features can be manifested in the landscape is numerous. The dynamic environments of the Fremont NF contribute to the complexity of mapping such a diverse study area and future use of the LTA units of the forest should be viewed in light these factors.

5.7.3 Implementation of LTA Unit Boundaries in the Fremont NF

Reliance on the improved SRI map units was critical for the delineation of LTA map units. These SRI units more consistently followed the landforms described in their attribute tables after modification. As the foundations of the LTA units, corrected SRI units allowed for a more accurate LTA map than would have been constructed if only unmodified SRI units were available.

Thirteen LTA map units were produced based on modified SRI units and landform, but it is important to note that some smaller landforms present in the forest are not described in the LTA tables. For example, small lacustrine benches are present in various locations throughout the forest. However, because these landforms do not cover land extents comparable to other LTA units delineated, an LTA unit for this landform was not constructed. During the delineation process, LTA map units were combined on the scale of thousands of acres, rather than hundreds, which would have been required by smaller landforms. As some of the SRI units themselves cover an acreage size larger than hundreds of acres, it was impractical to delineate LTA units smaller than this size.

Generally, LTA units include at least five different SRI units, and in areas of the forest where the terrain is more complex, this number increases.

If a future survey of the forest is ever undertaken, it is recommended that the smaller landforms should be described and delineated, as they may be of use in management practices. For instance, the lacustrine benches mentioned earlier are often ideal locations for agricultural endeavors. Many other small landforms in the forest likely present different management opportunities as well, but in the time allotted for this study, this next step in the analysis was not feasible.

The production of this LTA map unit was completed at the landscape scale of 1:100,000. The descriptions of LTA units are intended to reflect the major characteristics of each region, although small exceptions to the features listed occur in each LTA unit. Greatest emphasis was focused on geomorphology in the LTA units, but PNV helped to distinguish between boundaries where this factor was obscured. As a map unit intended for forest-level resource planning, the most significant environmental variables in the Fremont NF have been described, and will provide a way to interpret ecological processes spatially in the landscape.

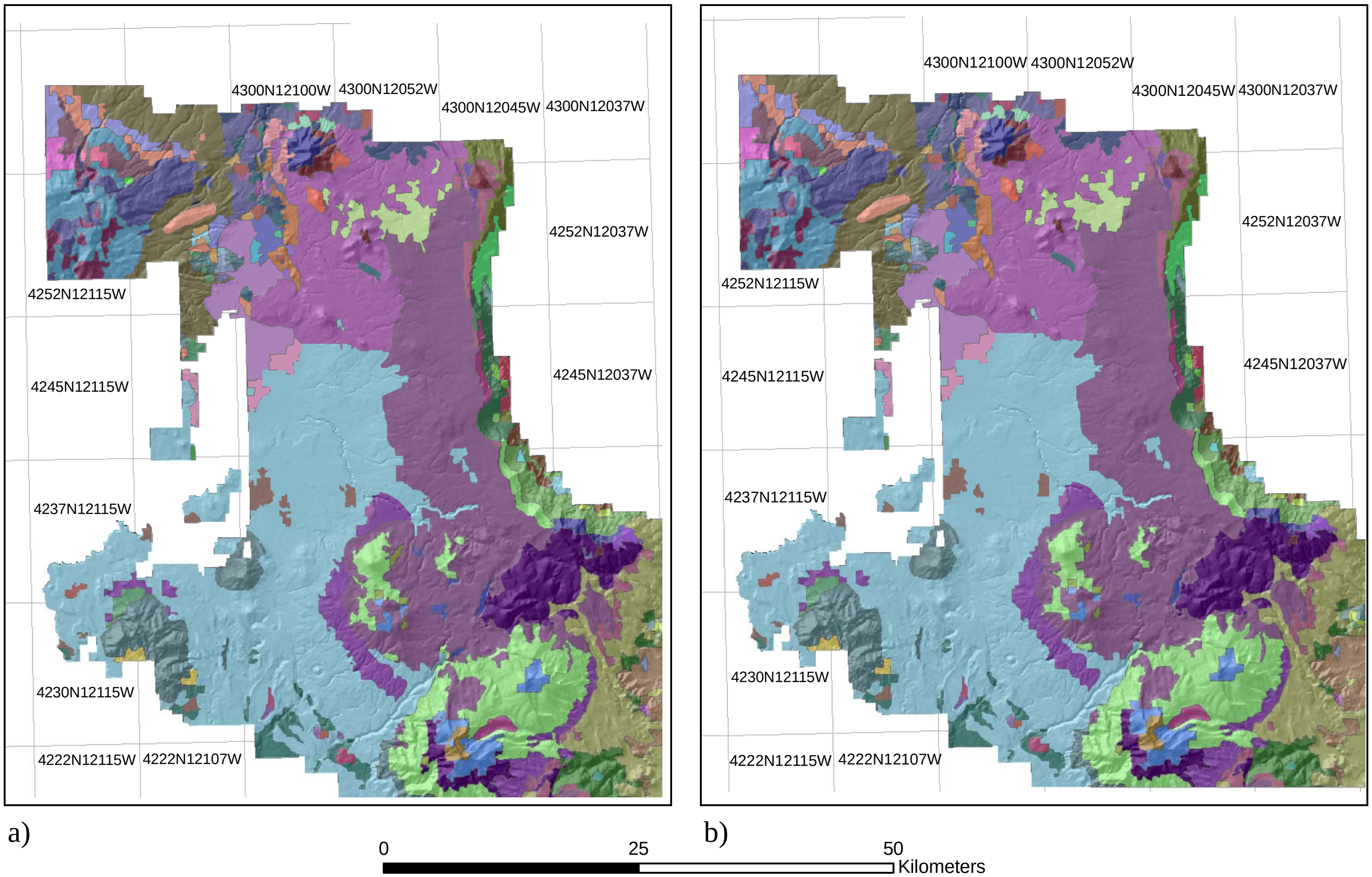

Figure 5- Predicted Maps of Fremont NF Zone 2a. Map a) shows the ground-truth soil units and Map b) shows the predicted soil units.

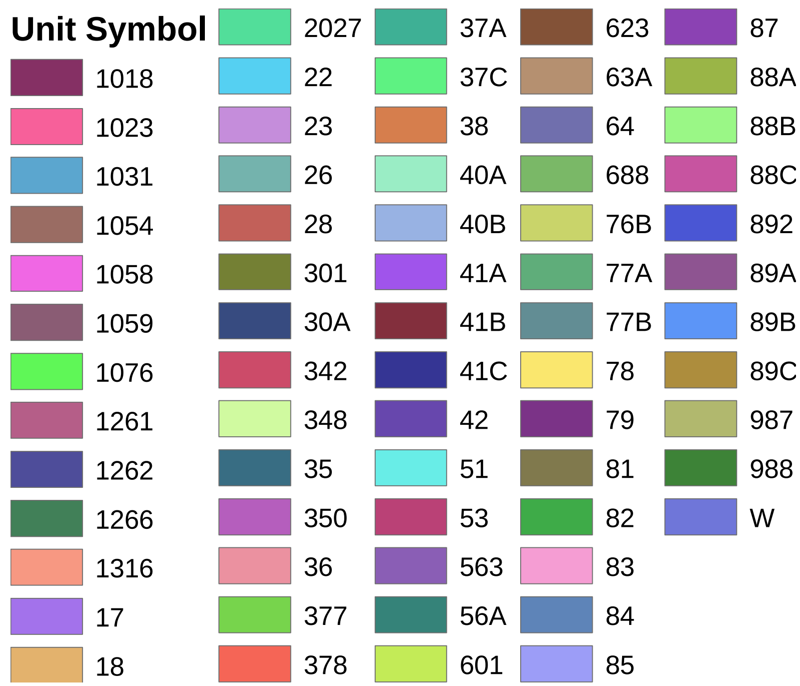

Figure 5A- Legend for Figure 5.

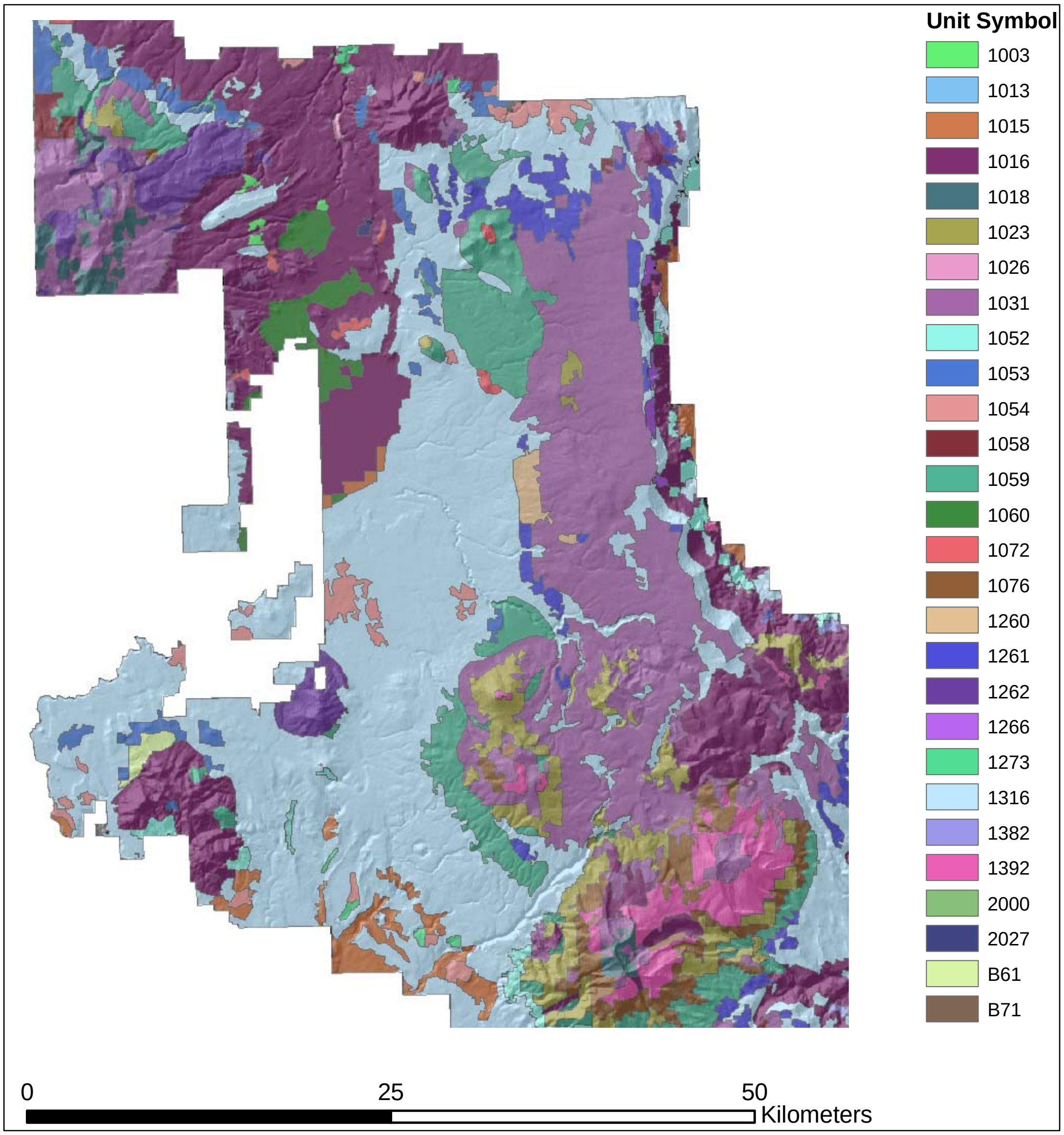

Figure 6- Predicted Map using EUI units.

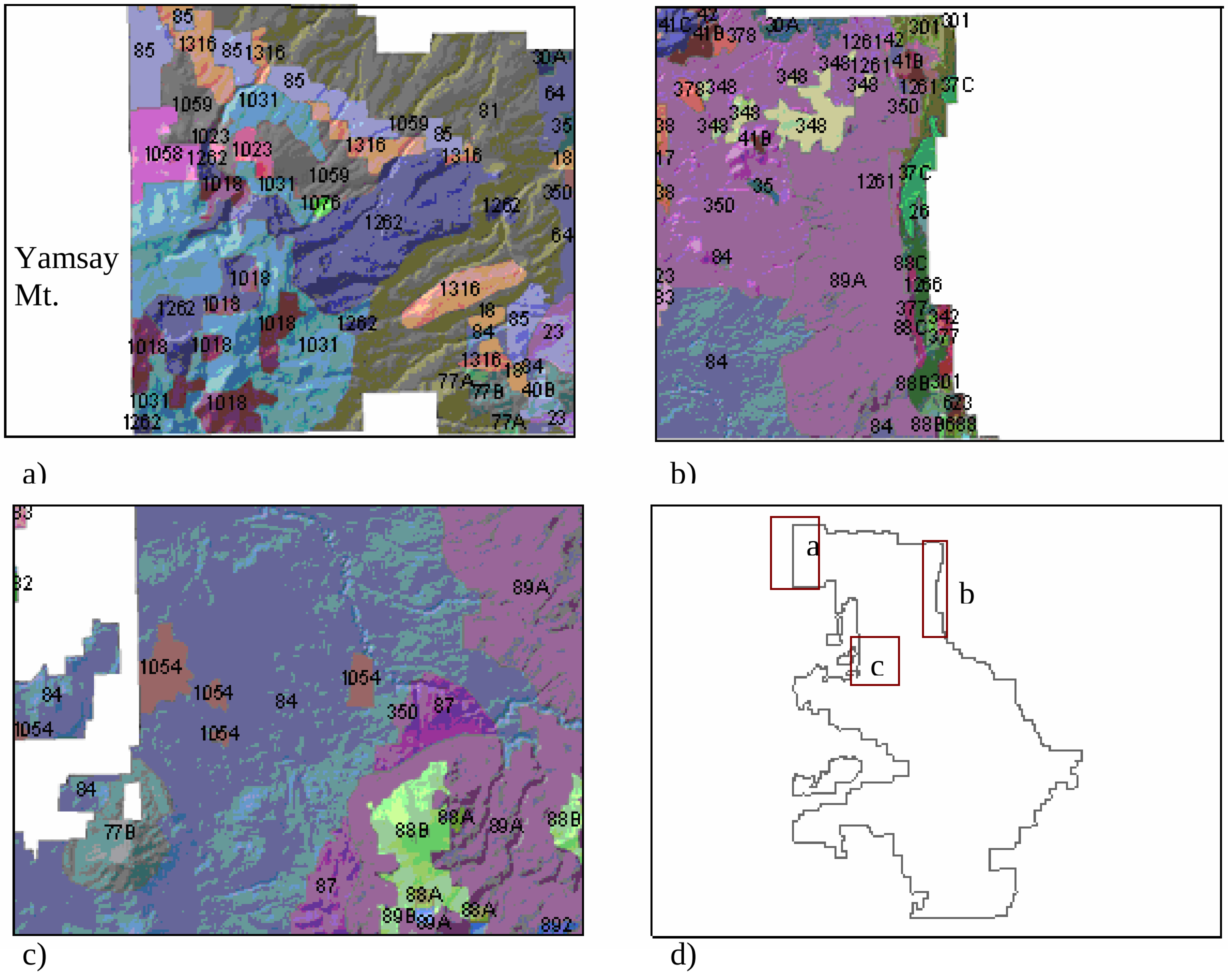

Figure 7- Locations of EUI units in Zone 2a. Map a) The remaining EUI units in the pumice plateau zone surrounding Yamsay Mountain. Map b) The EUI soil-creep units located on landslide deposits. Map c) EUI unit 1054 in scabrock areas near streams. Map d) The locations of EUI units in the Fremont NF.

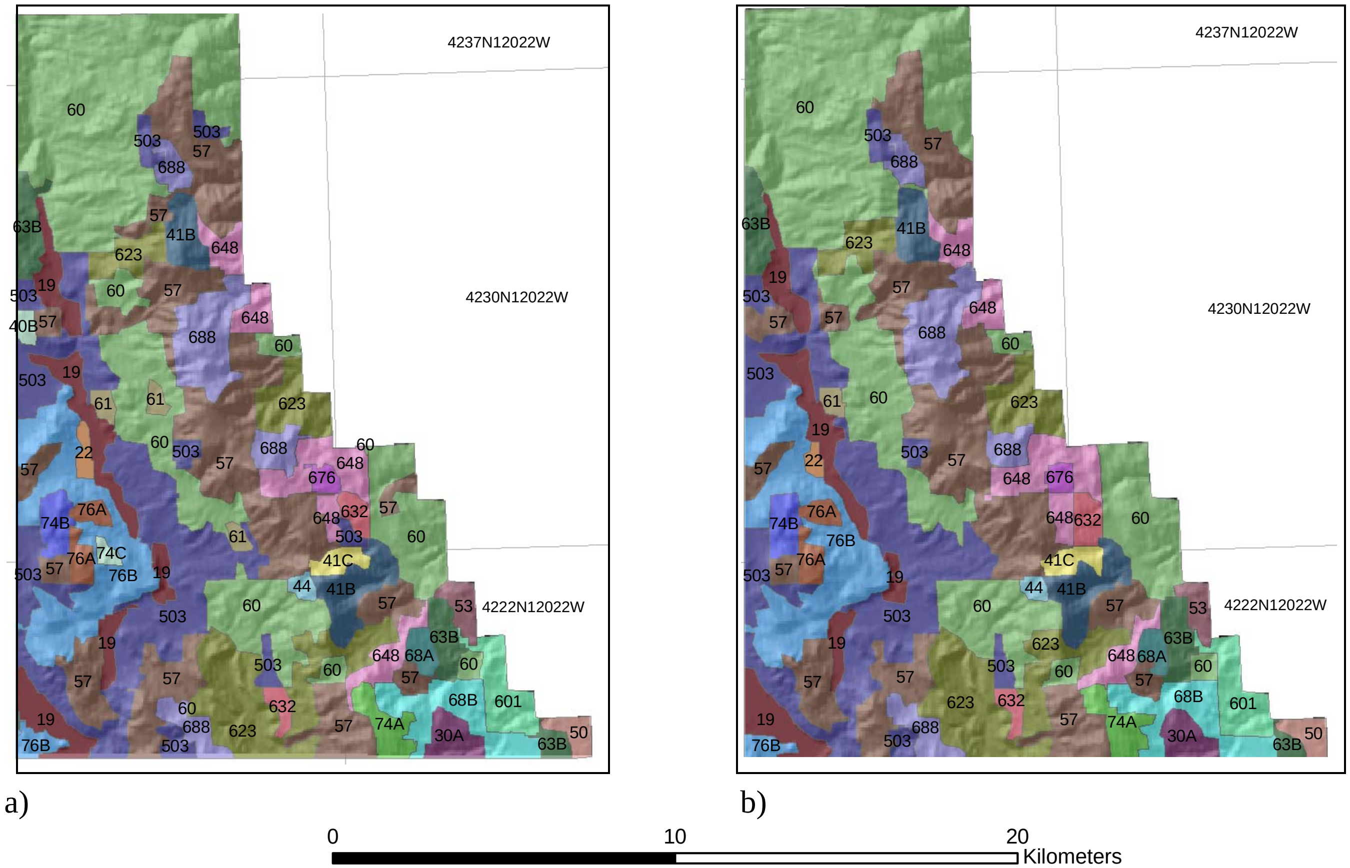

Figure 8- Predicted Maps of Zone 2b. Map a) shows the ground-truth image of Zone 2b and Map b) shows the predicted image of soil units.

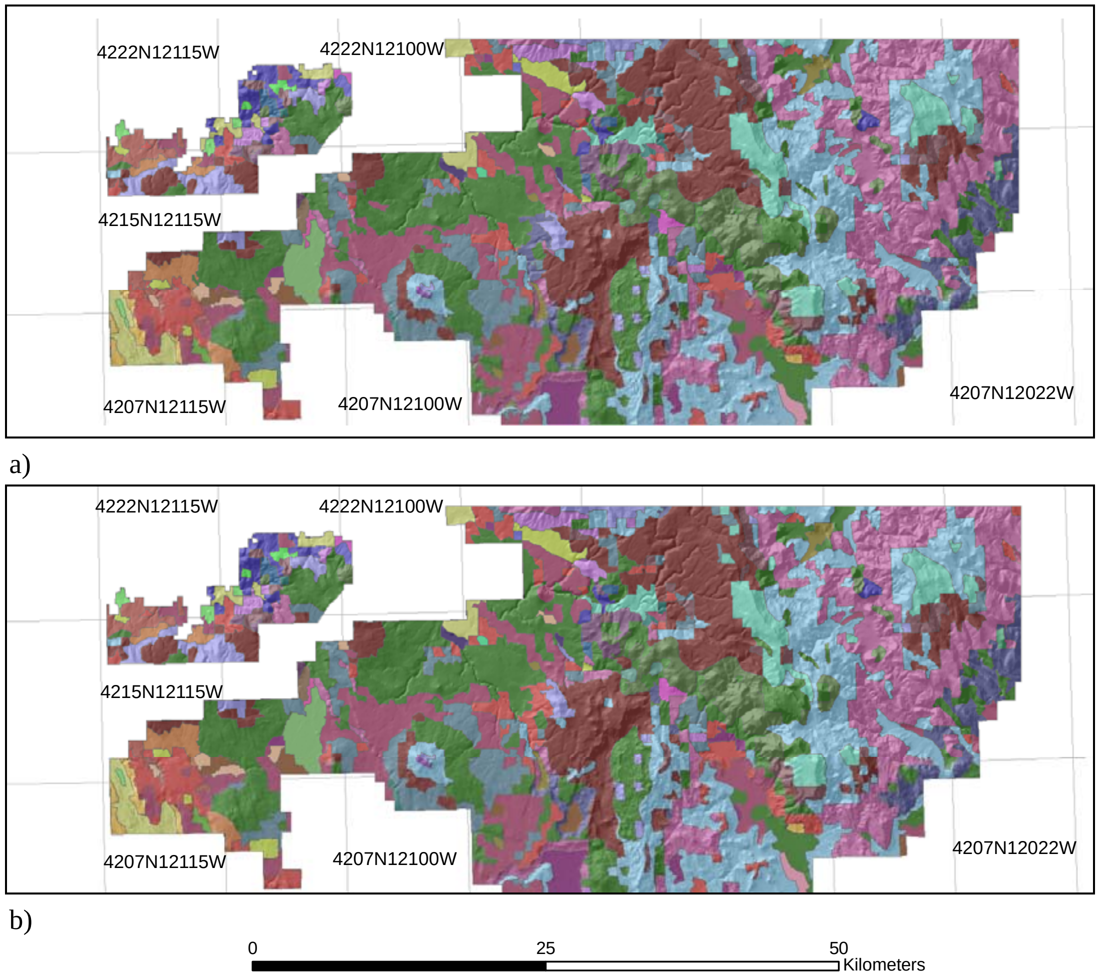

Figure 9- Predicted Maps of Zone 3c. Map a) shows the ground-truth image of Zone 3c and Map b) shows the predicted image of soil units.

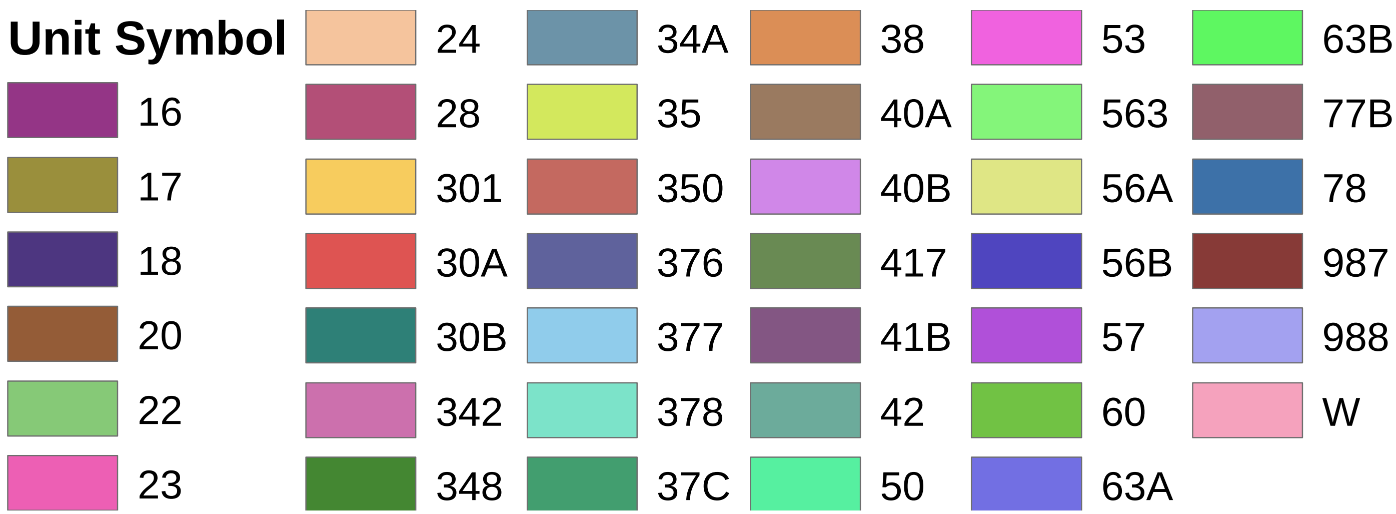

Figure 9A- Legend for Figure 9.

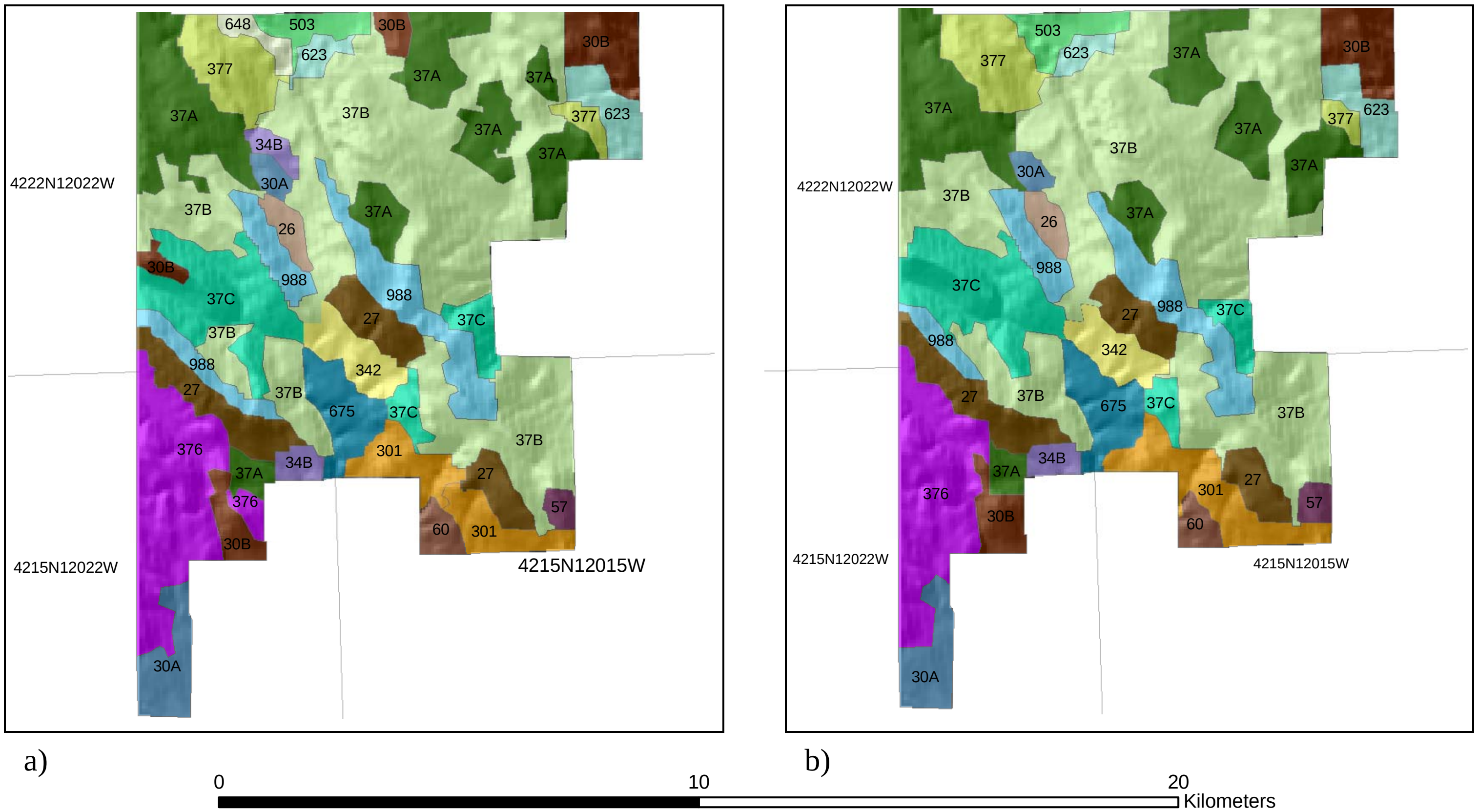

Figure 10- Predicted Maps of Zone 3d. Map a) shows the ground-truth image of Zone 3d and Map b) shows the predicted image of soil units.

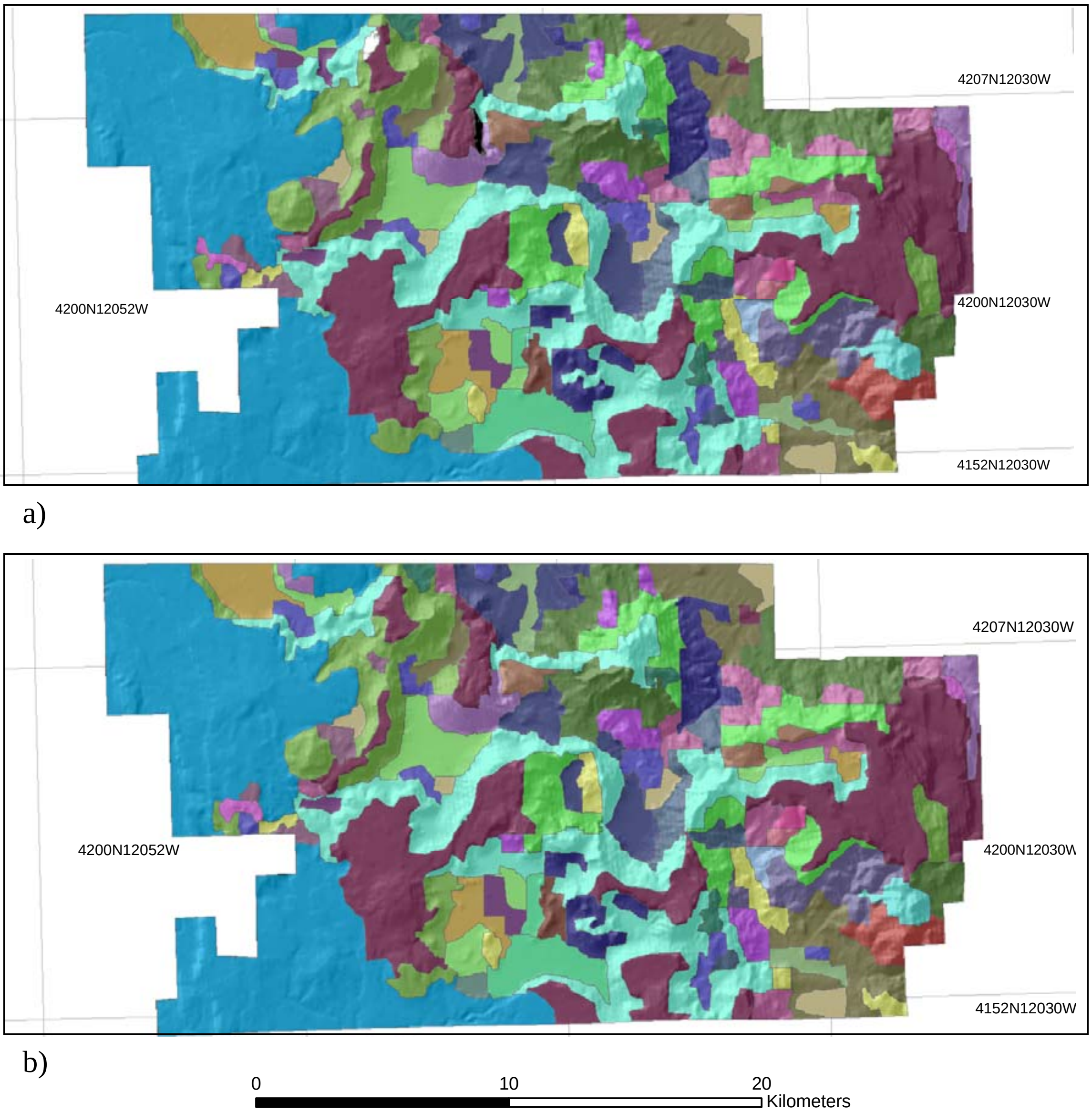

Figure 11- Predicted Maps of Zone 4. Map a) shows the ground-truth image of Zone 4 and Map b) shows the predicted image of soil units.

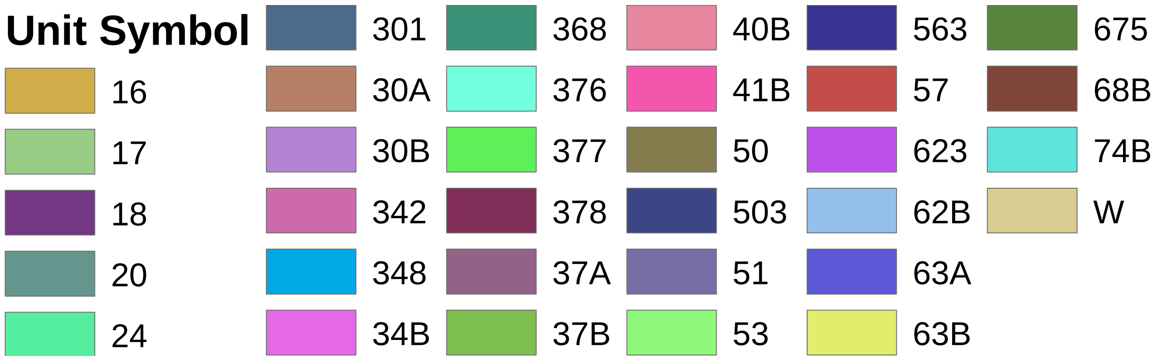

Figure 11A- Legend for Figure 11.

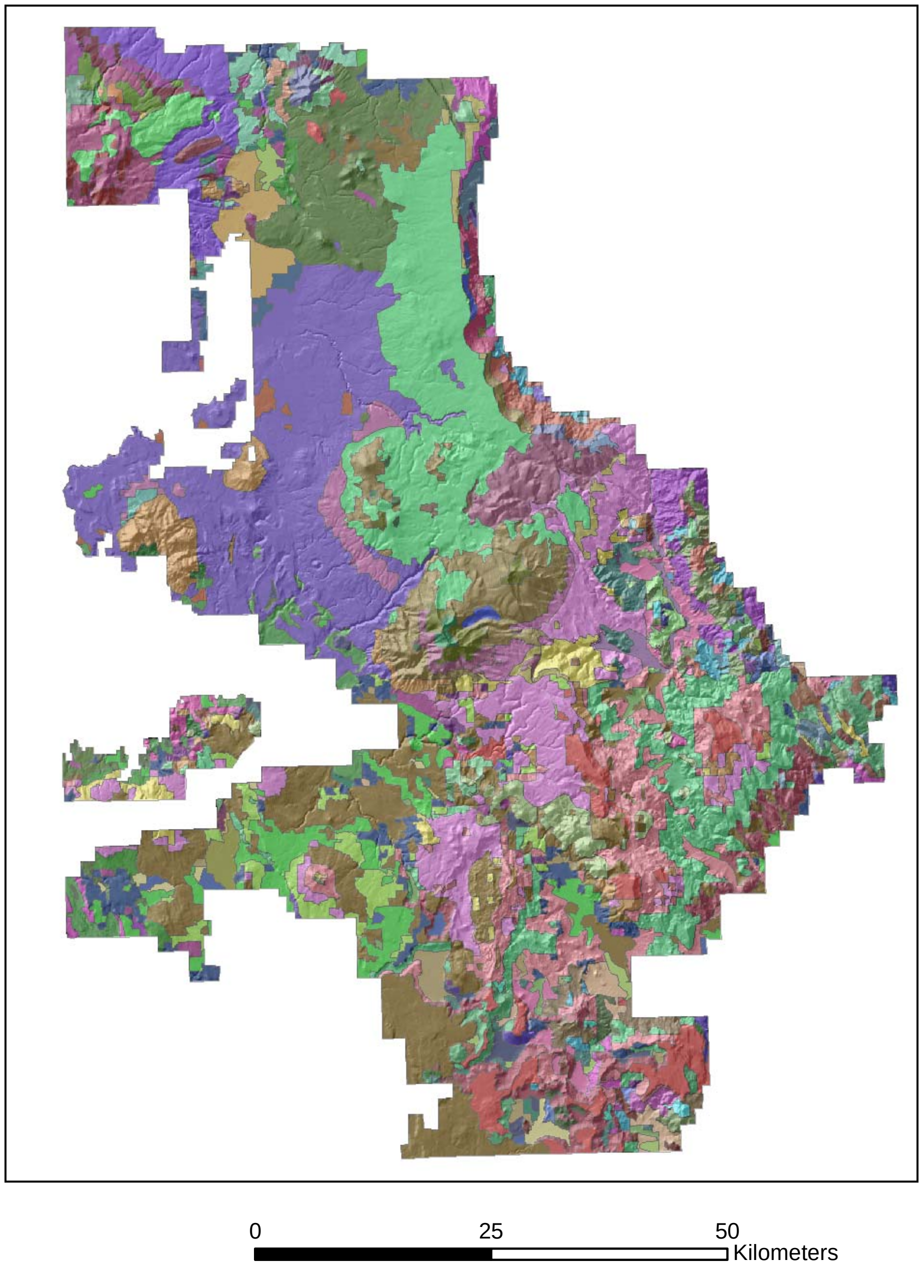

Figure 12- Prediction of the Entire Fremont NF.

Unit Symbol	18	348	40A	56B	688	84
1018	19	34A	40B	57	68A	85
1023	20	34B	417	60	68B	87
1031	2027	35	41A	601	74A	88A
1054	22	350	41B	61	74B	88B
1058	23	36	41C	623	76A	88C
1059	24	368	42	62B	76B	892
1076	26	376	44	632	77A	89A
1261	27	377	50	63A	77B	89B
1262	28	378	503	63B	78	89C
1266	301	37A	51	64	79	987
1316	30A	37B	53	648	81	988
16	30B	37C	563	675	82	W
17	342	38	56A	676	83	

Figure 12A- Legend for Figure 12.

Table 4- Summary of Statistics for Zones 2-4.

Zone	Units Predicted	Kappa Coefficient	Overall Accuracy (%)	Producer's Accuracy: Range (%)	Producer's Accuracy: Mean (%)	User's Accuracy: Range (%)	User's Accuracy: Mean (%)
Zone 2a	66 out of 67	0.97	98	59.1 - 100	91.8	82.6 - 100	94.8
Zone 2b	25 out of 26	0.95	96.2	33.5 - 100	90	79.3 - 100	93.8
Zone 3c	40 out of 40	0.97	97	68 - 100	93.6	85.7 - 100	95.4
Zone 3d	18 out of 19	0.93	94.3	74.9 - 99.8	89.1	82.5 - 100	92.1
Zone 4	33 out of 34	0.95	95.2	57.3 - 100	90.9	74.8 - 99.9	92.9

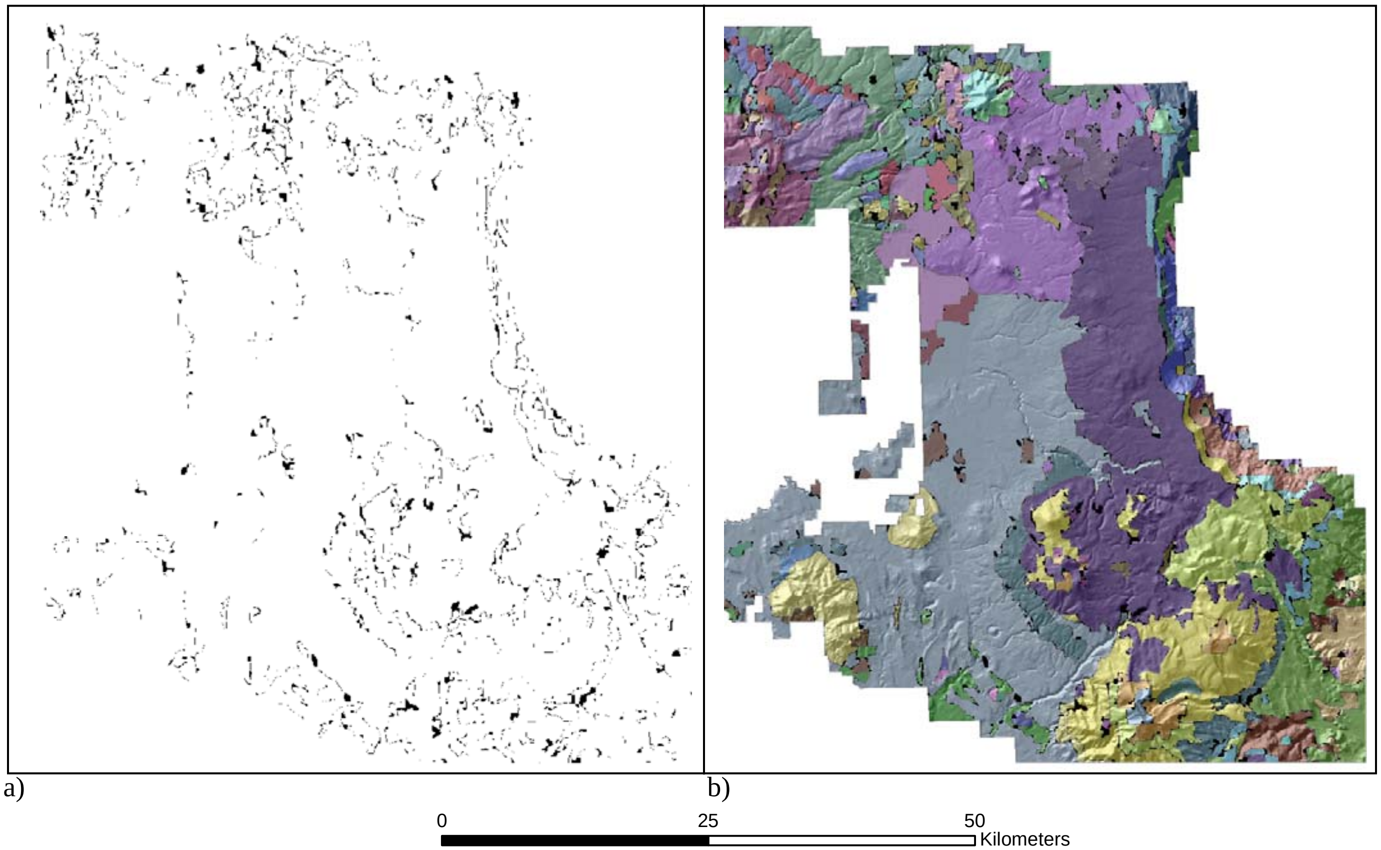

Figure 13- Zone 2a Error Map. Map a) Error map of Zone 2a. Map b) Predicted image overlaid with Zone 2a error map.

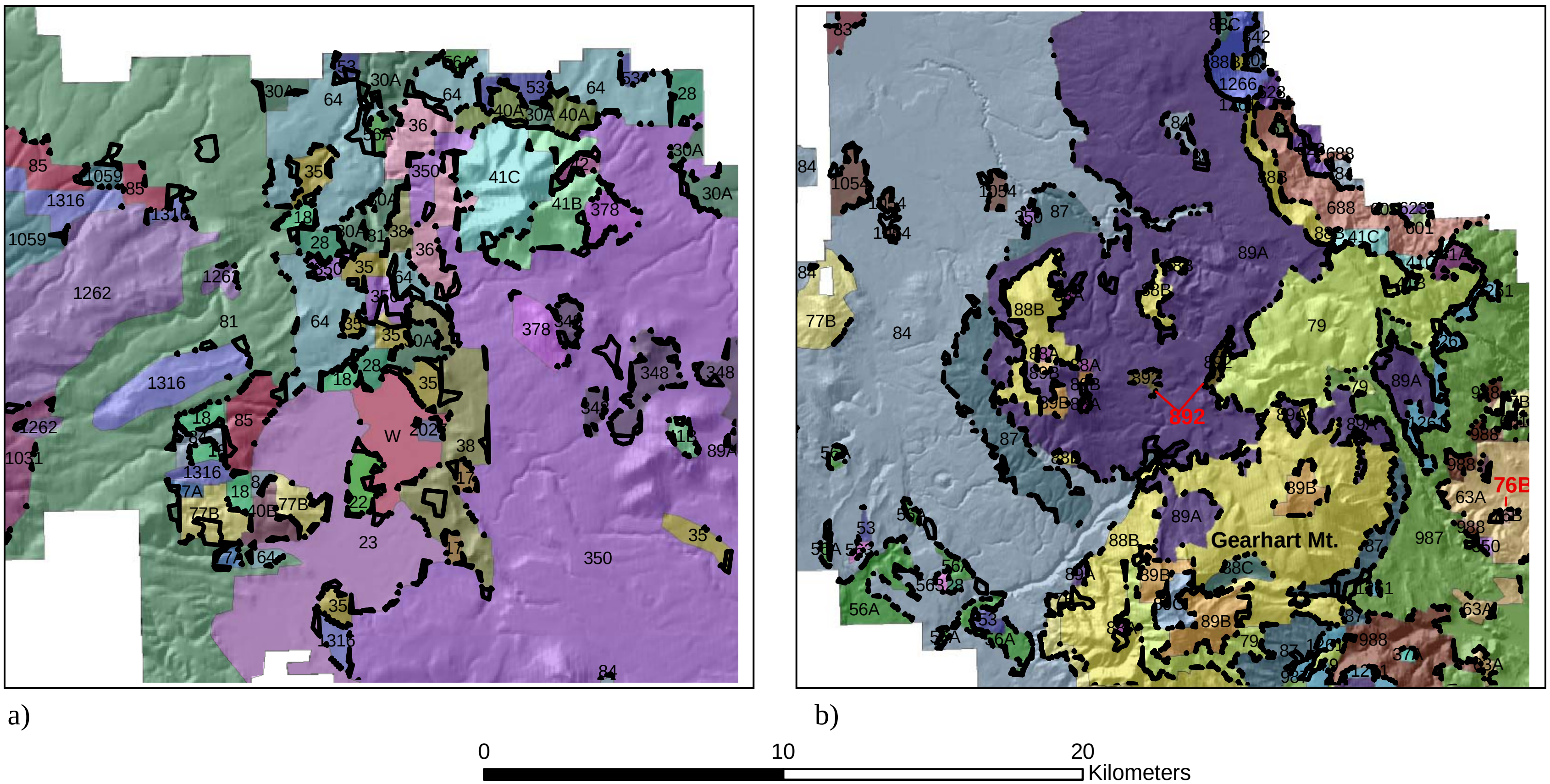

Figure 14- Areas of Concentrated Misclassification in Zone 2a. Map a) Northern region of Zone 2a showing misclassification around small SRI units. Map b) Misclassification error on Gearhart Mountain and surrounding complex terrain.

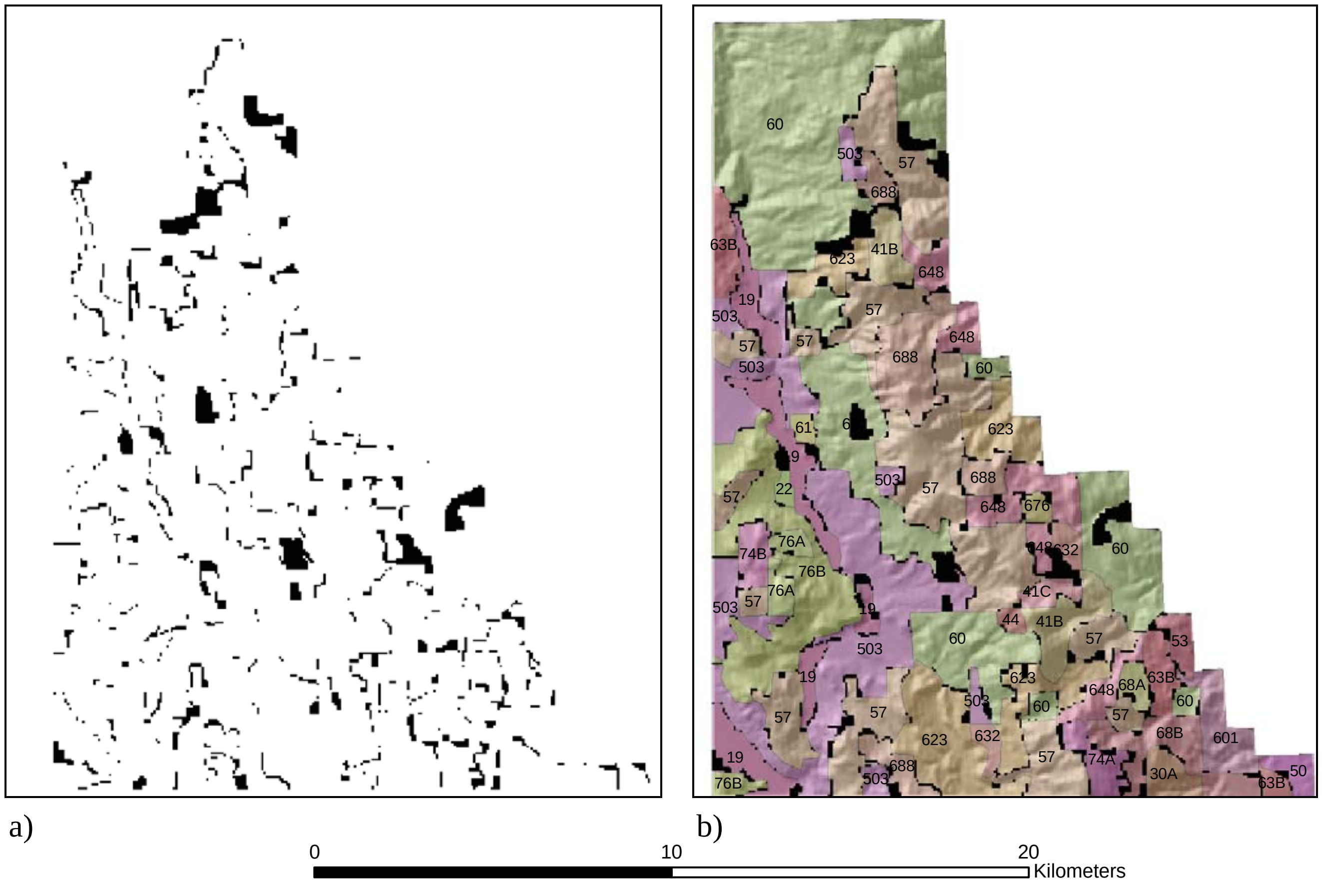

Figure 15- Zone 2b Error Maps. Map a) Error map of Zone 2b. Map b) Predicted image overlaid with Zone 2b error map.

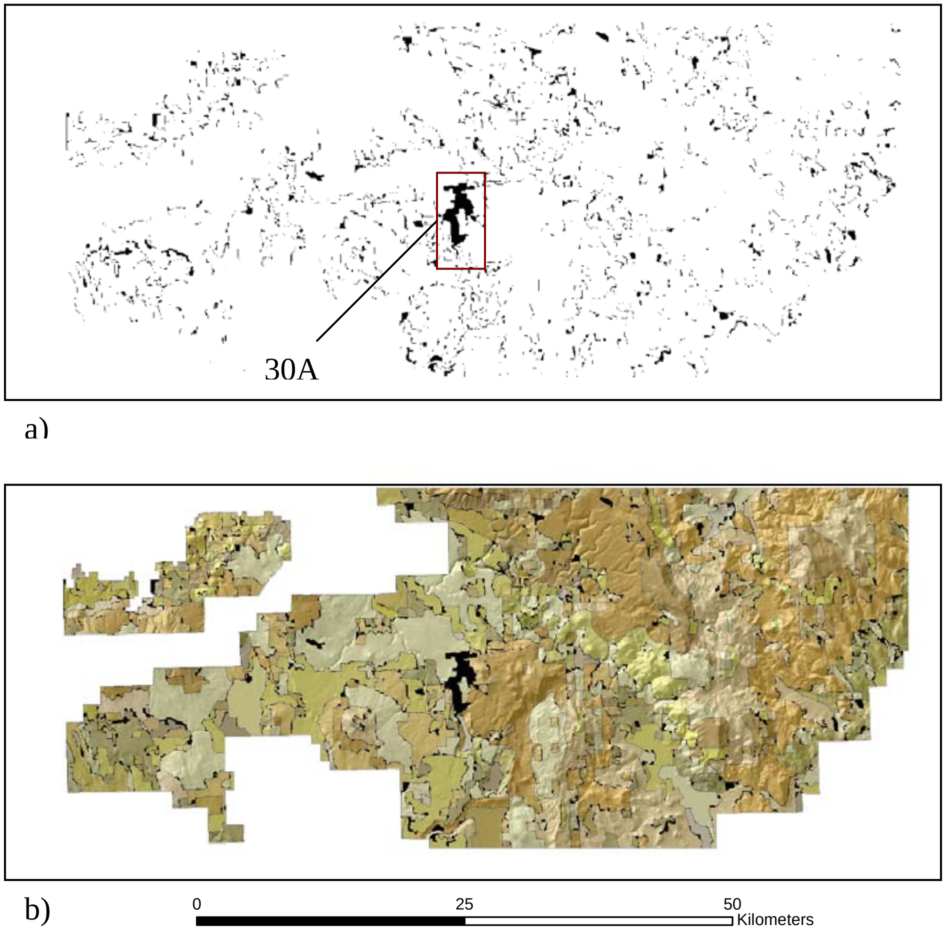

Figure 16- Zone 3c Error Maps. Map a) Error map of Zone 3c. Map b) Predicted image overlaid with Zone 3c error map.

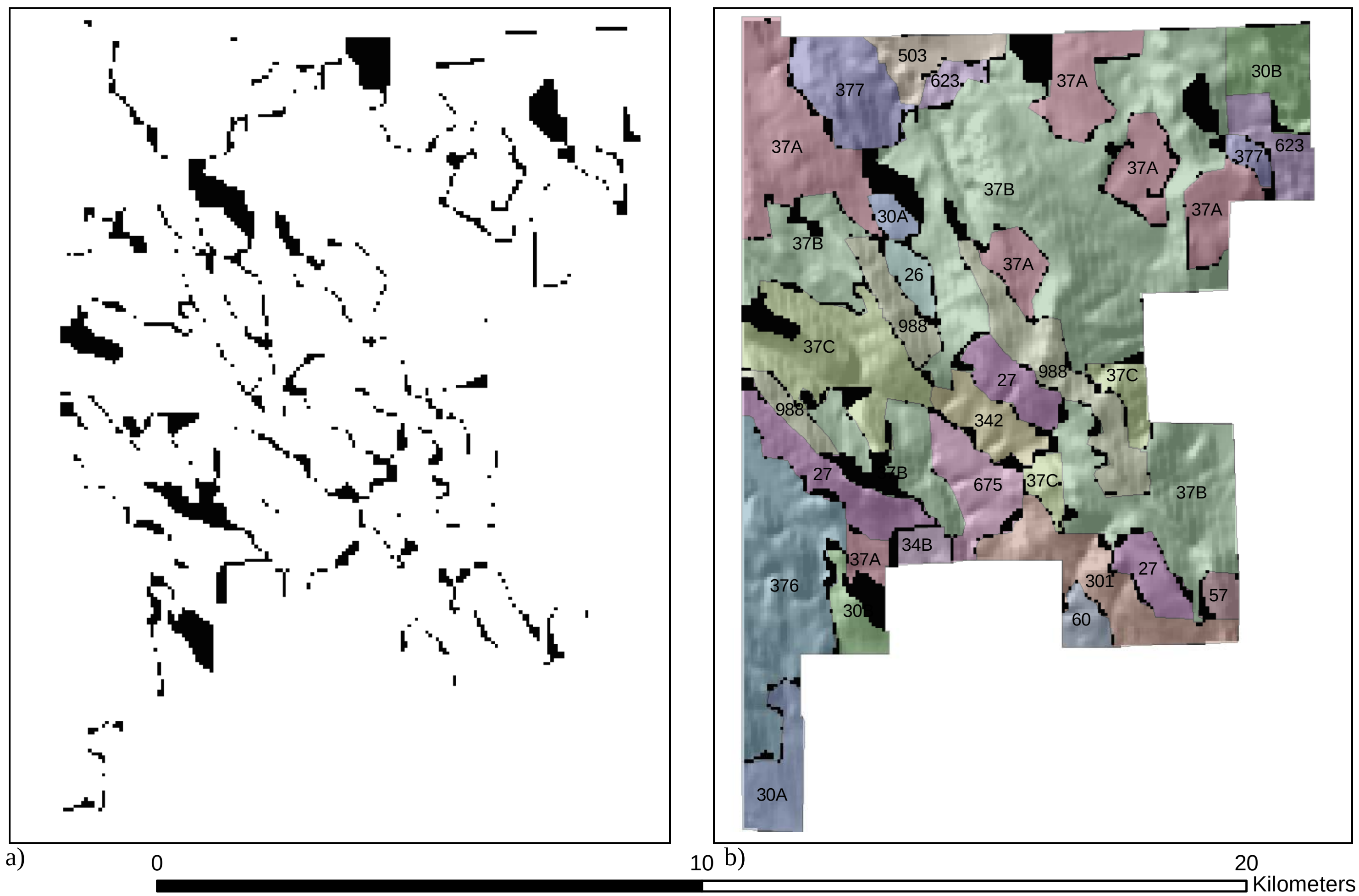

Figure 17- Zone 3d Error Maps. Map a) Error map of Zone 3d. Map b) Predicted image overlaid with Zone 3d error map.

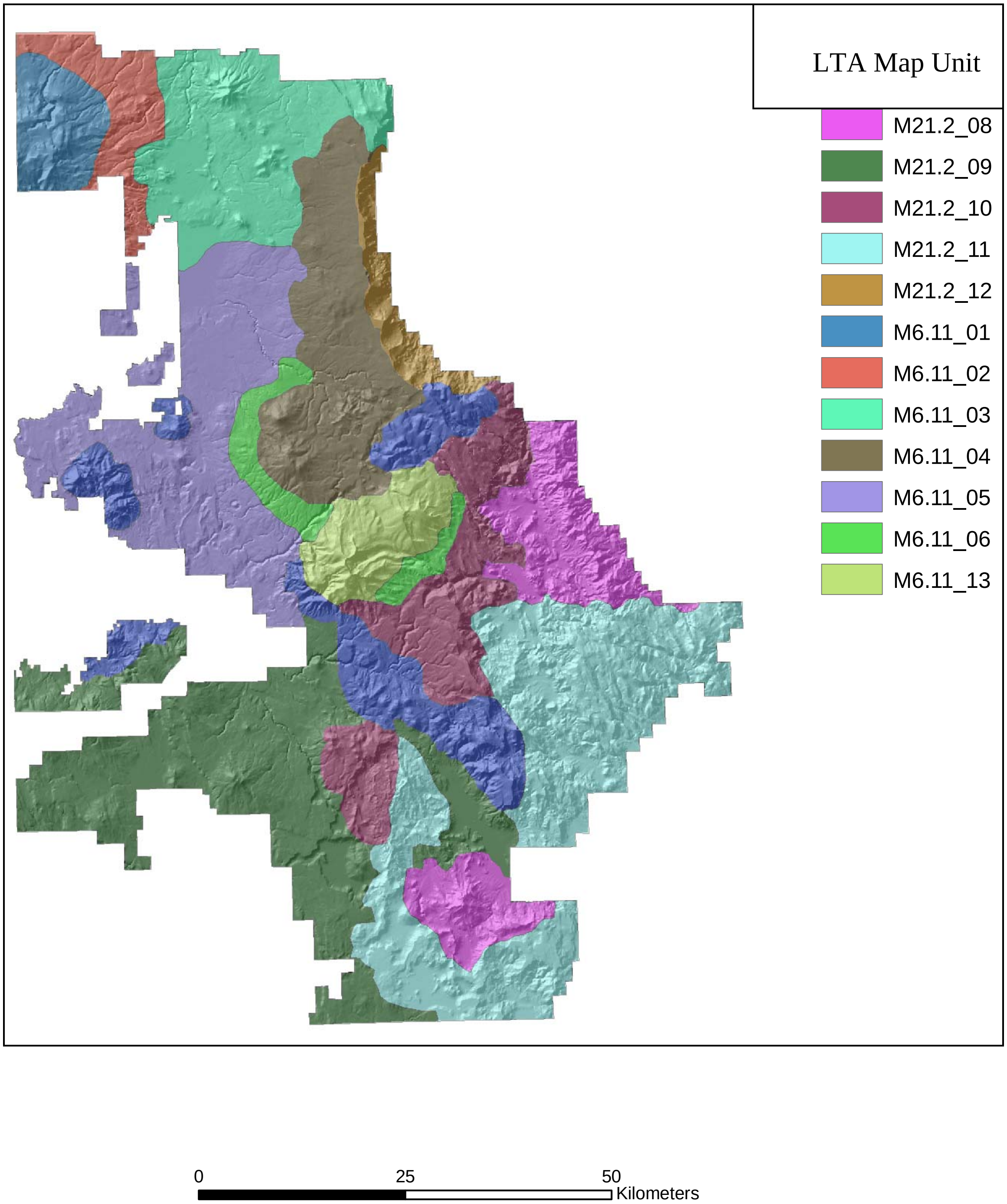

Figure 18- LTA Map Units of the Fremont NF.

Table 5- Soils in Landtype Association Units.

Soil Code	Subgroup	Great Group	Surface Texture	Regolith Texture	Depth to Bedrock (in)	Parent Material
16	Cumulic	Cryaquolls	moderately fine	moderately fine	60+	Alluvial and Colluvial Deposits
17	Pachic	Argixerolls	medium	moderately fine	40+	Alluvium Derived from Tuff and Breccia
18	Fluvaquentic	Haploaquolls	medium	moderately fine	40+	Alluvium Derived from Tuff, Breccia, and Basalt
19	Mollic	Xerofluvents	moderately coarse	moderately coarse	40+	Alluvium Derived from Tuff, Breccia, and Basalt
20	Typic	Chromoxererts	moderately fine	fine	40+	Lacustrine and Clay Deposits
22	Typic	Durochrepts	moderately coarse	moderately fine	15-40	Stream Deposited Alluvium Derived from Tuff, Breccia, Basalt, and Rhyolite
23	Entic	Haploxerolls	medium	medium	22-50	Stream Deposited Alluvium Derived from Tuff, Breccia, Basalt, and Rhyolite
24	Typic	Durixerolls	moderately fine	moderately fine	40+	Lacustrine Deposits Derived from Tuff and Basalt
26	Duric	Argixerolls	medium	moderately fine	40+	Colluvium from Basalt and Tuff
27	Pachic	Cryoborolls	moderately fine	moderately fine	20-50	Residuum from Basalt, Andesite, and Tuff
28	Lithic	Haploxeralfs	moderately fine	moderately fine	8-20	Basalt and Tuff Residuum
30A	Typic	Argixerolls	moderately fine	moderately fine	10-25	Bsalt, Andesite, and Tuff Residuum
30B	Typic	Argixerolls	moderately fine	moderately fine	10-25	Bsalt, Andesite, and Tuff Residuum
34A	Typic	Argixerolls	medium	moderately fine	25-48	Basalt and Tuff Residuum and Colluvium
34B	Typic	Argixerolls	medium	moderately fine	25-48	Basalt and Tuff Residuum and Colluvium

Table 5- Soils in Landtype Association Units (continued).

Soil Code	Subgroup	Great Group	Surface Texture	Regolith Texture	Depth to Bedrock (in)	Parent Material
35	Typic	Argixerolls	medium	moderately fine	25-48	Residuum from Tuff, Basalt, and Andesite
36	Typic	Argixerolls	medium	moderately fine	20-40	Residuum from Cinders and Tuff
37A	Typic	Argixerolls	moderately coarse	medium	25-48	Basalt, Andesite, and Tuff Residuum and Colluvium
37B	Typic	Argixerolls	moderately coarse	medium	25-48	Basalt, Andesite, and Tuff Residuum and Colluvium
37C	Typic	Argixerolls	moderately coarse	medium	25-48	Basalt, Andesite, and Tuff Residuum and Colluvium
38	Typic	Argixerolls	moderately coarse	moderately fine	20-40	Residuum from Basalt, Andesite, and Tuff
40A	Typic	Xerorthents	moderately coarse	moderately coarse	30-50	Rhyolite and Tuff Residuum and Colluvium
40B	Typic	Xerorthents	moderately coarse	moderately coarse	30-60	Rhyolite and Tuff Residuum and Colluvium
41A	Typic	Xerorthents	moderately coarse	coarse	30-60	Rhyolite and Tuff Residuum and Colluvium
41B	Typic	Xerorthents	moderately coarse	coarse	30-60	Rhyolite and Tuff Residuum and Colluvium
41C	Typic	Xerorthents	moderately coarse	coarse	30-60	Rhyolite and Tuff Residuum and Colluvium
42	Typic	Xerorthents	moderately coarse	moderately coarse	50+	Colluvium from Rhyolite and Tuff
44	Typic	Cryorthents	moderately coarse	moderately coarse	30-60	Rhyolite and Tuff Residuum and Colluvium
50	Lithic	Argixerolls	moderately fine	fine	6-20	Tuff Residuum
51	Typic	Rhodoxeralfs	fine	moderately fine	18-36	Tuff Residuum

Table 5- Soils in Landtype Association Units (continued).

Soil Code	Subgroup	Great Group	Surface Texture	Regolith Texture	Depth to Bedrock	Parent Material
53	Lithic	Xerorthents	medium	medium	6-20	Ash-Flow Tuff Residuum
56A	Pachic	Haploxerolls	medium	moderately fine	18-34	Tuff and Breccia Residuum
56B	Pachic	Haploxerolls	medium	moderately fine	16-34	Tuff and Breccia Residuum
57	Typic	Xerorthents	moderately coarse	moderately fine	8-32	Breccia, Mudflow, and Tuff Residuum
60	Typic	Argixerolls	medium	moderately fine	20-36	Breccia, Tuff, and Tuffaceous Sandstone Residuum
61	Fluvaquentic	Haploxerolls	medium	medium	50-120	Breccia and Tuff Colluvium
62B	Typic	Argixerolls	medium	moderately fine	22-34	Residuum from Tuff, Breccia, and Tuffaceous Sedimentary Rocks
63A	Entic	Haploxerolls	moderately coarse	moderately coarse	22-40	Tuff and Breccia Residuum
63B	Entic	Haploxerolls	moderately coarse	moderately coarse	22-40	Tuff and Breccia Residuum
64	Typic	Haploxerepts	medium	medium	25-45	Residuum from Tuff, Ashy Diatomite, and Tuffaceous Siltstone and Sandstone
68A	Entic	Haploxerolls	moderately coarse	coarse	22-50	Ash-Flow Tuff and Breccia Residuum and Colluvium
68B	Entic	Haploxerolls	moderately coarse	coarse	22-50	Ash-Flow Tuff and Breccia Residuum and Colluvium
74A	Typic	Xerorthents	coarse	coarse	25-40	Residuum and Colluvium from Rhyolitic Breccia
74B	Typic	Xerorthents	coarse	coarse	25-40	Residuum and Colluvium from Rhyolitic Breccia
76A	Typic	Xerorthents	moderately coarse	coarse	24-40	Residuum and Colluvium from Rhyolitic Breccia
76B	Typic	Xerorthents	moderately coarse	coarse	24-40	Residuum and Colluvium from Rhyolitic Breccia
77A	Typic	Xerorthents	coarse	coarse	40-70	Ash over Rhyolite Residuum and Colluvium
77B	Typic	Xerorthents	coarse	coarse	40-70	Ash over Rhyolite Residuum and Colluvium
78	Typic	Xerorthents	coarse	coarse	40-65	Ash over Rhyolite Residuum

Table 5- Soils in Landtype Association Units (continued).

Soil Code	Subgroup	Great Group	Surface Texture	Regolith Texture	Depth to Bedrock (in)	Parent Material
79	Typic	Xerorthents	coarse	coarse	35-65	Ash over Rhyolite Residuum
81	Typic	Xerorthents	coarse	coarse	20-40	Ash over Basalt and Tuff Residuum
82	Typic	Xerorthents	coarse	moderately coarse	50+	Ash over Basalt and Tuff Derived Valley Fill Deposits
83	Aquic	Xerorthents	coarse	moderately coarse	50+	Ash over Basalt and Tuff Derived Valley Fill Deposits
84	Typic	Xerorthents	coarse	coarse	35-70	Ash Overlying Basalt and Tuff Residuum
85	Typic	Xerorthents	coarse	coarse	35-65	Ash Overlying Basalt and Tuff Residuum
87	Typic	Xerorthents	coarse	coarse	35-65	Ash Overlying Buried Basalt and Tuff Residuum
88A	Typic	Xerorthents	coarse	coarse	28-60	Ash Overlying Basalt and Tuff Residuum and Colluvium
88B	Typic	Xerorthents	coarse	coarse	35-65	Ash Overlying Basalt and Tuff Residuum and Colluvium
88C	Typic	Xerorthents	coarse	coarse	35-65	Ash Overlying Basalt and Tuff Residuum and Colluvium
89A	Typic	Cryorthents	coarse	coarse	40-75	Ash Overlying Basalt and Tuff Residuum and Colluvium
89B	Typic	Cryorthents	coarse	coarse	40-75	Ash Overlying Basalt and Tuff Residuum and Colluvium
89C	Typic	Cryorthents	coarse	coarse	40-75	Ash Overlying Basalt and Tuff Residuum and Colluvium
1018	Xeric	Vitricryands	moderately coarse	coarse	69+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra
1023	Xeric	Vitricryands	moderately coarse	coarse	71+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra
1031	Xeric	Vitricryands	moderately coarse	coarse	69+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra

Table 5- Soils in Landtype Association Units (continued).

Soil Code	Subgroup	Great Group	Surface Texture	Regolith Texture	Depth to Bedrock (in)	Parent Material
1054	Vitrandic	Durixerolls	medium	moderately fine	54+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra
1058	Xeric	Vitricryands	coarse	moderately coarse	79+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra
1059	Xeric	Vitricryands	coarse	moderately coarse	79+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra
1076	Xeric	Vitricryands	coarse	moderately coarse	79+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra
1261	Alfic	Vitricryands	coarse	moderately coarse	57+	Colluvium Derived from Volcanic Rock or Tephra
1262	Alfic	Vitricryands	coarse	moderately coarse	41+	Colluvium Derived from Volcanic Rock or Tephra
1266	Humic	Vitricryands	coarse	moderately coarse	41+	Rubble Land Consisting of Cobbles, Stones, or Boulders Derived from Volcanic Rock
1316	Xeric	Vitricryand	coarse	moderately coarse	65+	Volcanic Ash and Pumice Derived from Dacite over Residuum Weathered from Volcanic Rock or Tephra
2027	Humic	Cryaquepts	medium	medium	36+	Alluvium over Grassy Organic Material

Table 6-Landtype Association Landforms.

LTA	Landform	Bedrock	Slope Gradient (%)	Depth to Bedrock (in)
M6.11_01	Air-fall Tephra Fields Mantling Lava Flows and Shield Volcanoes	Rhyolite and Dacite	0-15	79+
M6.11_02	Plateaus and Tablelands	Olivine Basalt; Silicic Ash-Flow Tuff; Silicic Vent Rocks	0-15	20-70
M6.11_03	Plateaus and Tablelands	Olivine Basalt; Basalt; Silicic Vent Rocks; Lacustrine and Fluvial Rocks	0-15	10-60
M6.11_04	Plateaus and Tablelands associated with Wide Basins and Eruptive Centers	Basalt; Mafic Vent Deposits; Mafic and Intermediate Vent Rocks	0-15	40-75
M6.11_05	Plateaus and Tablelands	Olivine Basalt; Basalt	0-10	35-70
M6.11_06	Slope Ridges and Side Slopes in Transition Zone Locations	Olivine Basalt; Mafic and Intermediate Vent Rocks	5-30	35-65
M21.2_07	Moderately Steep Slopes on Dome-Shaped Uplifts	Silicic Vent Rocks; Basalt; Rhyolite and Dacite	16-40	35-70
M21.2_08	Highly Dissected Domes, Ridges, and Side Slopes	Rhyolitic Tuff; Tuffaceous Sedimentary Rocks and Lava Flows; Clastic Rocks and Andesite Flows	10-50	6-120
M21.2_09	Basalt Lava and Tuff Plateaus or Tablelands	Olvine Basalt; Basalt	0-15	8-48
M21.2_10	Plateaus and Tablelands	Basalt	0-15	25-60
M21.2_11	Dissected Basaltic Eruptive Centers, Shield Volcanoes, and Block Fault Scarps	Basalt	16-40	22-50
M21.2_12	Moderately Steep Ridges and Soil-creep Slopes	Tuffaceous Sedimentary Rocks; Tuffs; Pumicites and Silicic Flows; Landslide and Debris-Flow Deposits; Basalt and Andesite	16-40	22-50
M6.11_13	Moderately Steep Slopes on Basaltic Eruptive Centers, Shield Volcanoes, and Block Faults	Mafic and Intermediate Vent Rocks	16-40	28-75

Table 7- Landtype Association Summary of Landscape Features.

Map Unit Code	Map Unit Long Name	Bedrock Geology: Primary	Bedrock Geology: Secondary	Bedrock Geologic Age	Surficial Geology	Surficial Geology: Origin	Landform	Soil	Potential Natural Vegetation
M6.11_01	Pumice Plateau Forest	Igneous (all)	Rhyolite and Dacite	Pliocene and Miocene (all)	Residuum	Volcanic Ash and Pumice	Air-Fall Tephra Fields Mantling Lava Flows and Shield Volcanoes, 0-15% Slope	Xeric Vitricryand	White Fir (Abies concolor)
M6.11_02	Pumice and Ash Transition Zone	Igneous (all)	Olivine Basalt; Silicic Ash-Flow Tuff; Silicic Vent Rocks	Pliocene and Miocene (all)	Residuum	Basalt, Interbedded Tuff, Volcanic Ash	Plateaus and Tablelands, 0-15% Slope	Typic Xerorthents	Ponderosa Pine (Pinus ponderosa)
M6.11_03	Ashy Scabland Plateaus	Igneous; Igneous; Sedimentary	Olivine Basalt; Basalt; Silicic Vent Rocks; Lacustrine and Fluvial Rocks	Pliocene, Miocene; Miocene; Pleistocene	Colluvium and Residuum; Alluvium	Basalt or Andesite, Ryholitic Ash-Flow Tuff, Ashy Diatomite and Lacustrine Tuffaceous Siltstone, Hard Breccia; Rhyolite-Dacite Ash-Flow Tuff, Tuffaceous Sedimentary Rock	Plateaus and Tablelands, 0-15% Slope	Typic Argixerolls, Lithic Haploxeralfs, Typic Haploxerepts, Entic Haploxerolls	Ponderosa Pine (Pinus ponderosa)
M6.11_04	Ashy Basins and Plateaus	Igneous (all)	Basalt; Mafic Vent Deposits; Mafic and Intermediate Vent Rocks	Miocene; Pleistocene, Pliocene, Miocene; Pliocene, Miocene	Colluvium and Residuum	Basalt, Volcanic Ash	Plateaus and Tablelands Associated with Wide Basins and Eruptive Centers, 0-15% Slope	Typic Cryorthents	Lodgepole Pine (Pinus contorta)
M6.11_05	Basalt Plateaus and Valleys	Igneous (all)	Olivine Basalt; Basalt	Pliocene, Miocene; Miocene	Colluvium and Residuum	Basalt, Massive Tuff, Volcanic Ash	Plateaus and Tablelands, 0-10% Slope	Typic Xerorthents	Ponderosa Pine (Pinus ponderosa)

Table 7- Landtype Association Summary of Landscape Features (continued).

Map Unit Code	Map Unit Long Name	Bedrock Geology: Primary	Bedrock Geology: Secondary	Bedrock Geologic Age	Surficial Geology	Surficial Geology: Origin	Landform	Soil	Potential Natural Vegetation
M6.11_06	Ashy Mountain Transition Zone	Igneous (all)	Olivine Basalt; Mafic and Intermediate Vent Rocks	Pliocene and Miocene (all)	Colluvium and Residuum	Basalt or Andesite, Massive Tuff, Volcanic Ash	Slope Ridges and Side Slopes in Transition Zone Locations, 5-30% Slope	Typic Xerorthents	Ponderosa Pine (Pinus ponderosa)
M21.2_07	Rhyolite Domes	Igneous (all)	Silicic Vent Rocks; Basalt; Rhyolite and Dacite	Pliocene, Miocene, Oligocene; Miocene; Pliocene, Miocene	Colluvium and Residuum	Foliated Rhyolite, Rhyolitic Breccia, Welded Tuff, Obsidian, Andesite, Basalt	Moderately Steep Slopes on Dome-Shaped Uplifts, 16-40% Slope	Typic Xerorthents	Mixed Conifer
M21.2_08	Pyroclastic Buttes	Igneous and Sedimentary; Igneous	Rhyolitic Tuff, Tuffaceous Sedimentary Rocks, and Lava Flows; Clastic Rocks and Andesite Flows	Miocene, Oligocene; Oligocene, Eocene, Paleocene	Colluvium and Residuum	Massive Ash-Flow Tuff, Massive Olive Breccia, Tuffaceous Sandstone, Basalt, Rhyolite	Highly Dissected Domes, Ridges, and Sideslopes, 10-50% Slope	Typic Argixerolls, Typic Xerorthents, Lithic Argixerolls, Lithic Xerorthents, Entic Haploxerolls	Juniper (Juniperus occidentalis) and Ponderosa Pine (Pinus ponderosa)
M21.2_09	Stony Flats	Igneous (all)	Olivine Basalt; Basalt	Pliocene, Miocene; Miocene	Residuum	Basalt or Andesite, Interbedded tuff	Basalt Lava and Tuff Plateaus or Tablelands, 0-15% Slope	Typic Argixerolls, Lithic Haploxeralfs	Juniper (Juniperus occidentalis) and Ponderosa Pine (Pinus ponderosa)

Table 7- Landtype Association Summary of Landscape Features (continued).

Map Unit Code	Map Unit Long Name	Bedrock Geology: Primary	Bedrock Geology: Secondary	Bedrock Geologic Age	Surficial Geology	Surficial Geology: Origin	Landform	Soil	Potential Natural Vegetation
M21.2_10	Stony and Ashy Plateaus	Igneous(all)	Basalt	Miocene	Colluvium and Residuum	Basalt or Andesite, Massive Tuff, Volcanic Ash	Lava Plateaus and Tablelands, 0-15% Slope	Typic Argixerolls, Typic Xerorthents	Mixed Conifer
M21.2_11	Pyroclastic Ridges	Igneous and Sedimentary; Igneous	Rhyolitic Tuff, Tuffaceous Sedimentary Rocks, Lava Flows; Basalt	Miocene, Oligocene, Eocene; Miocene	Colluvium and Residuum	Basalt or Andesite, Tuffaceous Sedimentary Rock, Massive Ash-Flow Tuff, Breccia	Dissected Basaltic Eruptive Centers, Shield Volcanoes, and Block Fault Scarps, 16-40% Slope	Typic Argixerolls, Mollic Haploxeralfs, Entic Haploxerolls	Mixed Conifer
M21.2_12	Landslide Deposits	Igneous and Sedimentary; Igneous	Tuffaceous Sedimentary Rocks, Tuffs, Pumicites, and Silicic Flows; Landslide and Debris-Flow Deposits; Basalt and Andesite	Miocene; Holocene, Pleistocene; Miocene	Colluvium and Residuum	Rhyolitic Breccia with Tuff, Welded Tuff, Andesite, Massive Ash-Flow Tuff	Moderately Steep Ridges and Soil Creep Slopes, 16-40% Slope	Humic Vitricryand, Mollic Haploxeralfs, Entic Haploxerolls, Typic Xerorthents	Mixed Conifer
M6.11_13	Ashy Ridges	Igneous (all)	Mafic and Intermediate Vent Rocks	Pliocene and Miocene (all)	Colluvium and Residuum	Basalt or Andesite, Interbedded Tuff, Volcanic Ash	Moderately Steep Slopes on Basaltic Eruptive Centers, Shield Volcanoes, and Block Faults, 16-40% Slope	Typic Xerorthents	Mixed Conifer

CONCLUSIONS

This study involved two main objectives. The first objective was to predict the soils of the Fremont NF and to derive a landscape model by which this could be done consistently. The second objective was to delineate LTA map units for the forest that were based off of the information obtained in the landscape model. Both of these goals were completed and conclusions involving each objective are discussed below.

Beginning with the first task, soils in the Fremont NF were successfully predicted by extracting a soil-landscape model using DTA. This prediction model proved to be more consistent in classifying soils and identifying landforms than the original SRI map of the forest. During the prediction process, however, some areas of concern did arise and were mainly due to limitations in the training data that was available for the forest. The majority of the problems associated with training data were due to an overabundance of SRI units, which did not consistently follow landforms or other landscape boundaries, and resulted in subsequent mislabeling of units in initial prediction maps. These issues were overcome with modifications to the training data. The most important of these modifications involved the addition of EUI units as training data to correct for landform and the elimination of many SRI units within the forest. These improvements to the final predictive map were supplemented by knowledge of the study area, which was obtained through research and field-checking.

The second task of delineating LTA unit boundaries within the forest was also performed successfully. In total, thirteen different LTA map units were made, which stratified the landscape into homogenous regions. Accompanying attribute tables describing the significant landscape features within each region of the forest were made as well. Special attention was given to the environmental variables of soils and landforms, because these variables have a considerable impact on various ecosystems throughout the forest. Furthermore, providing detailed information about these landscape features will help determine the way the forest is managed for the productivity of its natural resources.

In completing this research, it is clear that there are many factors to consider when using a predictive mapping approach to derive a landscape model. Thorough knowledge of the area of interest and the ability to identify the strengths and weaknesses of the software used is of utmost importance. Accurate survey data is needed as well. As seen in this study, the better the initial survey data, the better the results of a prediction. Nonetheless, this method of mapping provides a unique opportunity for those who desire to have information about large areas of land in a relatively short period of time. Maps made by predictive mapping will help to reduce the amount of time needed for surveying and will also allow for a more transparent analysis of locations of interest.

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APPENDIX

Table A1- Confusion Matrix Generated for Zone 2a. Overall accuracy and the kappa coefficient are indicated in the upper left-hand corner of the table. Producer's and user's accuracy are given in percentage and pixel number for each soil code.

Overall Accuracy = (1160663/1184113) 98.0196%
Kappa Coefficient = 0.9762

Class	**Prod. Acc. (Percent)**	**User Acc. (Percent)**	**Prod. Acc. (Pixels)**	**User Acc. (Pixels)**
Unclassified	99.97	99.98	417446/417553	417446/417533
1018 [Red]	90.69	91.77	4393/4844	4393/4787
1023 [Green]	92.09	96.24	768/834	768/798
1031 [Blue]	96.84	96.46	16699/17244	16699/17312
1054 [Yellow]	83.77	93.85	3650/4357	3650/3889
1058 [Cyan]	99.47	95.69	2066/2077	2066/2159
1059 [Magenta	89.33	96.77	4975/5569	4975/5141
1076 [Maroon]	92.64	94.38	151/163	151/160
1261 [Sea Green]	88.23	91.39	8088/9167	8088/8850
1262 [Purple]	98.16	96.67	12602/12838	12602/13036
1266 [Coral]	95.31	96.63	5730/6012	5730/5930
1316 [Aquamarine]	92.64	96.95	6430/6941	6430/6632
17 [Orchid]	83.09	95.39	290/349	290/304
18 [Sienna]	88.14	94.37	1122/1273	1122/1189
2027 [Chartreus]	97.30	90.00	144/148	144/160
22 [Thistle]	84.07	92.46	454/540	454/491
23 [Red1]	98.80	98.65	13781/13948	13781/13969
26 [Red2]	87.07	89.47	357/410	357/399
28 [Red3]	86.12	96.70	1756/2039	1756/1816
301 [Green1]	95.36	95.44	5732/6011	5732/6006
30A [Green2]	90.65	92.66	4973/5486	4973/5367
342 [Green3]	97.18	97.50	1207/1242	1207/1238
348 [Blue1]	91.77	94.63	7025/7655	7025/7424
35 [Blue2]	89.36	89.87	2217/2481	2217/2467
350 [Blue3]	98.06	97.76	59035/60204	59035/60387
36 [Yellow1]	92.30	94.02	2074/2247	2074/2206
377 [Yellow2]	93.57	93.79	393/420	393/419

Table A1- Confusion Matrix Generated for Zone 2a (continued).

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
378 [Yellow3]	95.97	96.10	1430/1490	1430/1488
37A [Cyan1]	96.20	96.72	177/184	177/183
37C [Cyan2]	95.35	96.87	3401/3567	3401/3511
38 [Cyan3]	95.48	90.43	3485/3650	3485/3854
40A [Magenta1	92.77	92.34	988/1065	988/1070
40B [Magenta2	87.90	97.53	712/810	712/730
41A [Magenta3	93.65	93.24	841/898	841/902
41B [Maroon1]	88.54	93.88	3299/3726	3299/3514
41C [Maroon2]	91.69	97.39	4361/4756	4361/4478
42 [Maroon3]	86.67	87.76	624/720	624/711
51 [Purple1]	83.07	82.63	157/189	157/190
53 [Purple2]	83.75	92.85	1546/1846	1546/1665
563 [Purple3]	75.61	97.80	400/529	400/409
56A [Orange1]	92.05	95.11	7933/8618	7933/8341
601 [Orange2]	80.76	92.56	684/847	684/739
623 [Orange3]	93.55	91.13	1828/1954	1828/2006
63A [Orange4]	98.69	97.38	8870/8988	8870/9109
64 [Sienna1]	95.98	92.32	8745/9111	8745/9472
688 [Sienna2]	95.93	95.82	8114/8458	8114/8468
76B [Sienna3]	60.33	96.69	146/242	146/151
77A [Thistle1]	91.29	96.94	2536/2778	2536/2616
77B [Thistle2	98.30	97.53	21778/22154	21778/22330
78 [Red]	99.46	97.88	1292/1299	1292/1320
79 [Green]	96.15	96.55	26061/27104	26061/26993
81 [Blue]	99.23	97.58	30947/31187	30947/31714
82 [Yellow]	88.94	97.25	177/199	177/182
83 [Cyan]	97.59	97.88	3922/4019	3922/4007
84 [Magenta]	99.10	98.37	181306/182954	181306/184314
85 [Maroon]	97.19	94.28	5836/6005	5836/6190
87 [Sea Green	95.38	96.10	19286/20220	19286/20068
88A [Purple]	77.42	88.11	689/890	689/782

Table A1- Confusion Matrix Generated for Zone 2a (continued).

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
88B [Coral]	96.32	96.44	45685/47428	45685/47372
88C [Aquamarine]	93.58	96.52	2332/2492	2332/2416
892 [Orchid]	59.13	93.18	806/1363	806/865
89A [Sienna]	98.55	97.22	122160/123961	122160/125651
89B [Chartreu	94.20	96.08	7208/7652	7208/7502
89C [Thistle]	93.64	92.29	1340/1431	1340/1452
987 [Red1]	97.30	97.71	35804/36797	35804/36643
988 [Red2]	97.44	96.70	8063/8275	8063/8338
W [Red3]	96.87	92.95	2136/2205	2136/2298

Table A2- Confusion Matrix Generated for Zone 2b. Overall accuracy and the kappa coefficient are indicated in the upper left-hand corner of the table. Producer's and user's accuracy are given in percentage and pixel number for each soil code.

Overall Accuracy = (97215/101086) 96.1706%
Kappa Coefficient = 0.9510

Class	**Prod. Acc. (Percent)**	**User Acc. (Percent)**	**Prod. Acc. (Pixels)**	**User Acc. (Pixels)**
Unclassified	100.00	100.00	41837/41837	41837/41837
19 [Red]	91.39	88.80	2378/2602	2378/2678
22 [Green]	62.78	100.00	113/180	113/113
30A [Blue]	94.76	94.17	452/477	452/480
41B [Yellow]	94.35	97.95	1436/1522	1436/1466
41C [Cyan]	96.48	88.67	274/284	274/309
44 [Magenta]	95.07	96.43	135/142	135/140
50 [Maroon]	100.00	94.06	301/301	301/320
503 [Sea Green]	91.05	92.89	7026/7717	7026/7564
53 [Purple]	86.92	98.46	319/367	319/324
57 [Coral]	90.62	94.21	10037/11076	10037/10654
601 [Orchid]	96.77	98.31	870/899	870/885
61 [Sienna]	33.50	95.65	132/394	132/138
623 [Chartreus]	95.39	93.89	4239/4444	4239/4515
632 [Thistle]	97.03	79.29	425/438	425/536
648 [Red2]	94.20	92.72	2241/2379	2241/2417
676 [Red3]	87.50	87.01	154/176	154/177
688 [Green1]	92.76	93.09	2397/2584	2397/2575
68A [Green2]	83.39	97.57	241/289	241/247
68B [Green3]	91.05	93.46	1200/1318	1200/1284
74A [Blue1]	90.06	86.55	489/543	489/565
74B [Blue2]	93.85	95.37	412/439	412/432
76A [Blue3]	97.40	97.61	449/461	449/460
76B [Yellow]	96.02	96.24	3453/3596	3453/3588
63B [Red1]	90.25	93.51	1138/1261	1138/1217
60 [Aquamarine]	98.09	93.21	15067/15360	15067/16165

Table A3- Confusion Matrix Generated for Zone 3c. Overall accuracy and the kappa coefficient are indicated in the upper left-hand corner of the table. Producer's and user's accuracy are given in percentage and pixel number for each soil code.

Overall Accuracy = (691333/712800) 96.9884%
Kappa Coefficient = 0.9656

Class	**Prod. Acc. (Percent)**	**User Acc. (Percent)**	**Prod. Acc. (Pixels)**	**User Acc. (Pixels)**
Unclassified	99.97	100.00	188308/188366	188308/188316
17 [Green]	91.02	90.49	1864/2048	1864/2060
28 [Sea Green]	94.80	94.64	38790/40919	38790/40986
350 [Red1]	89.21	94.04	3505/3929	3505/3727
40A [Blue1]	97.88	98.85	601/614	601/608
16 [Red]	97.26	97.24	4800/4935	4800/4936
18 [Blue]	92.55	92.29	646/698	646/700
20 [Yellow]	96.50	94.69	2870/2974	2870/3031
22 [Cyan]	97.77	96.96	4465/4567	4465/4605
23 [Magenta]	68.03	93.26	249/366	249/267
24 [Maroon]	92.72	93.94	1797/1938	1797/1913
301 [Purple]	92.85	95.12	2064/2223	2064/2170
30A [Coral]	94.68	85.68	22742/24019	22742/26542
30B [Aquamarine]	86.59	93.79	846/977	846/902
342 [Orchid]	97.18	97.43	67071/69020	67071/68843
348 [Sienna]	96.54	96.45	93614/96967	93614/97057
34A [Chartreus]	93.85	95.18	22127/23576	22127/23247
35 [Thistle]	95.98	97.23	3821/3981	3821/3930
376 [Red2]	83.73	95.18	13545/16177	13545/14231
377 [Red3]	97.19	97.14	73526/75654	73526/75688
378 [Green1]	98.98	98.23	16564/16734	16564/16863
37C [Green2]	98.06	96.81	303/309	303/313
38 [Green3]	96.24	93.82	4842/5031	4842/5161
40B [Blue2]	97.92	97.27	4852/4955	4852/4988
417 [Orange1]	98.12	97.48	14562/14841	14562/14938
41B [Blue3]	95.28	96.27	2944/3090	2944/3058

Table A3- Confusion Matrix Generated for Zone 3c (continued).

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
42 [Yellow1]	94.24	99.53	638/677	638/641
50 [Yellow2]	97.81	100.00	179/183	179/179
53 [Yellow3]	95.70	95.48	867/906	867/908
563 [Cyan1]	88.71	87.90	966/1089	966/1099
56A [Cyan2]	96.18	96.11	7935/8250	7935/8256
56B [Cyan3]	93.41	95.39	5418/5800	5418/5680
57 [Magenta1]	92.75	86.49	128/138	128/148
60 [Magenta2]	94.13	98.19	433/460	433/441
63A [Magenta3	98.83	98.01	592/599	592/604
63B [Maroon1]	90.88	88.81	508/559	508/572
77B [Maroon2]	89.51	95.37	8117/9068	8117/8511
78 [Maroon3]	96.70	96.94	1202/1243	1202/1240
987 [Purple1]	98.14	96.73	62720/63911	62720/64838
988 [Purple2]	94.80	97.18	9377/9891	9377/9649
W [Purple3]	83.63	98.01	935/1118	935/954

Table A4- Confusion Matrix Generated for Zone 3d. Overall accuracy and the kappa coefficient are indicated in the upper left-hand corner of the table. Producer's and user's accuracy are given in percentage and pixel number for each soil code.

Overall Accuracy = (40899/43365) 94.3134%
Kappa Coefficient = 0.9294

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
Unclassified	99.87	99.96	15358/15378	15358/15364
30A [Yellow]	94.01	97.11	706/751	706/727
57 [Chartreus]	99.28	82.53	137/138	137/166
26 [Red]	87.17	87.95	197/226	197/224
27 [Green]	92.65	90.14	1399/1510	1399/1552
301 [Blue]	95.18	95.18	1006/1057	1006/1057
30B [Cyan]	74.90	84.75	928/1239	928/1095
342 [Magenta]	87.13	91.75	467/536	467/509
34B [Maroon]	48.25	82.50	165/342	165/200
376 [Sea Green]	90.87	97.04	2030/2234	2030/2092
377 [Purple]	88.71	95.34	880/992	880/923
37A [Coral]	90.37	93.14	3434/3800	3434/3687
37B [Aquamarine]	95.97	89.06	9042/9422	9042/10153
37C [Orchid]	91.11	87.97	1835/2014	1835/2086
503 [Sienna]	96.24	96.80	333/346	333/344
60 [Thistle]	91.74	99.11	222/242	222/224
623 [Red1]	90.34	95.81	617/683	617/644
675 [Red2]	95.63	89.19	635/664	635/712
988 [Red3]	84.20	93.90	1508/1791	1508/1606

Table A5- Confusion Matrix Generated for Zone 4. Overall accuracy and the kappa coefficient are indicated in the upper left-hand corner of the table. Producer's and user's accuracy are given in percentage and pixel number for each soil code.

Overall Accuracy = (170402/178917) 95.2408%
Kappa Coefficient = 0.9473

Class	**Prod. Acc. (Percent)**	**User Acc. (Percent)**	**Prod. Acc. (Pixels)**	**User Acc. (Pixels)**
Unclassified	99.99	99.90	29951/29954	29951/29980
24 [Cyan]	97.50	88.90	2147/2202	2147/2415
30A [Maroon]	93.08	90.61	1062/1141	1062/1172
348 [Coral]	98.85	98.54	31375/31739	31375/31840
368 [Orchid]	92.75	89.74	691/745	691/770
37A [Red1]	79.46	92.70	851/1071	851/918
16 [Red]	94.83	94.31	2604/2746	2604/2761
17 [Green]	85.68	83.55	1107/1292	1107/1325
18 [Blue]	57.34	92.88	730/1273	730/786
20 [Yellow]	92.69	96.54	279/301	279/289
301 [Magenta]	90.30	93.35	1797/1990	1797/1925
30B [Sea Green]	95.82	92.23	2088/2179	2088/2264
342 [Purple]	91.10	92.36	3785/4155	3785/4098
34B [Aquamarine]	65.35	74.83	330/505	330/441
376 [Sienna]	92.33	93.31	17459/18909	17459/18710
377 [Chartreus]	93.71	92.38	6598/7041	6598/7142
378 [Thistle]	97.74	95.07	21311/21804	21311/22416
37B [Red2]	91.81	95.08	7719/8408	7719/8118
40B [Red3]	92.23	96.94	190/206	190/196
41B [Green1]	97.32	93.04	254/261	254/273
50 [Green2]	94.92	92.78	5628/5929	5628/6066
503 [Green3]	93.63	92.76	4715/5036	4715/5083
51 [Blue1]	92.85	94.41	2414/2600	2414/2557
53 [Blue2]	91.15	86.20	3555/3900	3555/4124
563 [Blue3]	91.04	94.81	3524/3871	3524/3717

Table A5- Confusion Matrix Generated for Zone 4 (continued).

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
57 [Yellow1]	95.79	95.58	1342/1401	1342/1404
623 [Yellow2]	93.37	92.73	1888/2022	1888/2036
62B [Yellow3]	90.77	97.52	354/390	354/363
63A [Cyan1]	88.86	92.25	2298/2586	2298/2491
63B [Cyan2]	87.03	91.31	2007/2306	2007/2198
675 [Cyan3]	95.93	93.11	7451/7767	7451/8002
68B [Magenta1]	93.30	89.85	487/522	487/542
74B [Magenta2]	92.72	96.40	777/838	777/806
W [Magenta3]	89.44	96.74	1634/1827	1634/1689