BIOLOGICAL SOIL CRUSTS: ANALYSIS OF MONITORING TECHNIQUES AT THE YAKIMA TRAINING CENTER, WASHINGTON

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ABSTRACT

BIOLOGICAL SOIL CRUSTS: ANALYSIS OF MONITORING TECHNIQUES AT THE YAKIMA TRAINING CENTER, WASHINGTON

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Biological soil crusts are valuable components of the soil because they enhance numerous soil functions. Resource managers, including those at the Yakima Training Center (YTC), have shown growing interest in the ecological importance of soil crusts in relation to management decisions. The overall objectives of this study were to test sampling techniques for monitoring soil crust cover and composition in relation to YTC's Land Condition-Trend Analysis (LCTA). The research involved several interrelated steps: (a) use of several techniques to measure soil crust cover and composition; (b) collecting and analyzing related environmental variables including soil texture and chemistry, vascular plant cover, slope, and disturbance regime; and (c) utilizing community relationship software to analyze correlations between soil crust composition and environmental variables. Analysis results showed that use of soil crust morphological groups, combined with the point-line intercept technique, would be the most appropriate for sampling biological soil crusts along LCTA transects.

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CHAPTER 1

INTRODUCTION

Biological soil crusts, also known as biotic, cryptogamic, cryptobiotic, microphytic, or microbiotic soil crusts, are components of arid and semi-arid ecosystems world-wide (Belnap & Lange, 2001; Kaltenecker, 1997; Ponzetti & McCune, 2000). In North America, biological soil crusts are most prevalent in hot and cool deserts. Hot deserts are primarily located in the southwestern United States and are characterized by limited annual precipitation and extreme annual temperatures (Bailey, 1995). Cool deserts are located within the intermountain region of the western United States, starting in the Great Basin and extending into Canada, and are also characterized by limited annual precipitation, but lower annual temperatures when compared to hot deserts (Bailey).

Biological soil crusts are complex communities consisting of cyanobacteria, algae, bacteria, fungal hyphae, lichens, liverworts, and mosses inhabiting the bare soil interspaces of vascular plant communities (Belnap, Kaltenecker, et al., 2001; Belnap & Lange, 2001; Dunne, 1989; Ponzetti & McCune, 2000). In recent years, scientists and resource managers have shown growing interest in the ecological importance of soil crusts (Kaltenecker, 1997; Ponzetti, Youtie, Salzer, & Kimes, 1998; Rosentreter & Belnap, 2001).

Scientific research in this field suggests that ecological functions and roles played by crust components have numerous positive effects upon the landscape. These effects include (a) enhanced soil stability (Campbell, Seeler, & Golubic, 1989), (b) influences on soil moisture and water infiltration (Brotherson & Rushforth, 1983), (c) additions to nutrient cycles (Burns, 1983; Evans & Belnap, 1999), and (d) vascular plant influences such as increased seed germination and seedling establishment (St. Clair, Webb, & Johansen, 1984). Because of these reasons, resource managers across the western United States increasingly consider biological soil crusts during decision-making processes.

Problem

The Environment and Natural Resources Division (ENRD, 2001) at the U.S. Army's Yakima Training Center (YTC) has identified a need for indicators of disturbance on soil structure and function that may be useful in defining military training thresholds. Thresholds are designed to define stages of training land condition and are useful to YTC's land managers, because monitoring indicators in relation to specific thresholds can help to guide land use practices at YTC. Baseline biological soil crust information and routine monitoring may be useful in determining indicators of disturbance to soil structure and function, may help define thresholds, and thus, may be helpful in assessing training land condition.

On the YTC, long-term training land condition was recently assessed through the Land Condition-Trend Analysis (LCTA). Implemented in 1989, LCTA was designed to assess the army's training resource and provide long-term information regarding YTC's natural resources (Bern, 1996a). Within the last year, the U.S. Army has mandated a switch from LCTA to the army's Range and Training Land Assessment (RTLA), which is to focus more closely on specific military training impacts on military training lands. An approach using rapid qualitative monitoring, validated by quantitative data collection and the use of threshold sampling objectives is being stressed. At the YTC, this qualitative approach will likely be very similar to the monitoring manual, *Interpreting Indicators of Rangeland Health* (Pellant, Shaver, Pyke, & Herrick, 2005), which qualitatively compares existing conditions to reference conditions both validated by quantitative data collection. Continued monitoring of the YTC's existing LCTA plots is desired as the validation component of the qualitative RTLA approach.

In the past, biological soil crust data gathered as part of LCTA has been limited to an estimation of total moss and lichen cover using the point-line intercept sampling technique (Bern, 1996b). Detailed soil crust analysis may provide YTC resource managers with additional information regarding landscape condition if included as a component of the new RTLA process.

During the 2003 field season, the YTC and the Center for Ecological Management of Military Lands (CEMML) implemented the use of biological soil crust morphological groups as part of LCTA's ground cover monitoring. Morphological groups are broad characterizations of soil crust components that are relatively easily identified while conducting fieldwork. However, sampling of morphological groups has only been conducted using the point-line intercept technique, which has not been compared to other sampling techniques for collecting morphological group data. Dimensionality groups, another method of monitoring biological soil crusts, are even broader characterizations that take into account the structure or dimensionality of soil crust components. What is the most appropriate combination of methods and techniques for sampling biological soil crusts? More specifically, what is the difference between using morphological groups, dimensionality groups, and total crust cover in terms of monitoring long-term trends in biological soil crust composition of groundcover? Which sampling technique, line intercept or point-line intercept, for data collection of biological soil crust morphological group, dimensionality group, and total crust cover data are most appropriate for addition to the new RTLA monitoring methodology?

Purpose

The focus of this research will be to test the use of morphological groups and dimensionality groups in assessing the condition of biological soil crusts at the YTC as compared to total lichen/moss cover, using line intercept and point-line intercept sampling techniques. Also, I will attempt to provide resource managers at the YTC with a useful technique for assessing biological soil crust condition and evaluating that technique for possible inclusion as a component of RTLA. Specifically, the objectives of this research are as follows:

1. Collect baseline information on biological soil crusts at the YTC using line intercept and point-line intercept sampling techniques and three types of biological soil crust variables, morphological group, dimensionality group, and total crust cover characterizations.
2. Compare point-line intercept and line intercept techniques for effective and time efficient collection of biological soil crust morphological group, dimensionality group, and total crust cover data.
3. Compare morphological group, dimensionality group, and total crust cover data as it would be recorded within the ground cover component of existing

LCTA plots, in relation to environmental variables such as disturbance, soil texture and chemistry, topographic position, and vascular plant cover.

4. Provide recommendations for future biological soil crust monitoring in conjunction with YTC upland ecosystem monitoring, using the most appropriate methods.

Significance

Why should resource managers consider biological soil crusts when analyzing the condition and trend of the YTC landscapes? First, scientific evidence suggests that biological soil crusts are valuable components of the soil because they enhance numerous soil functions. This, in turn, affects vascular plant communities through increased soil moisture, improved seed germination and seedling establishment, and greater soil nutrient levels. Biological soil crusts also provide sanctuary for numerous taxa of microflora and fauna including algae, bacteria, diatoms, nematodes, various other soil inhabitants, and micorrhizal fungi (Anderson & Rushforth, 1976; Ashley, Rushforth, & Johansen, 1985; Johansen, Ashley, & Rayburn, 1993).

Secondly, research in this field provides evidence suggesting that the composition of soil crust communities may be an indicator of landscape condition and soil stability in relation to time since disturbance. Biological soil crusts follow a general successional pathway following disturbance (Belnap, Kaltenecker, et al., 2001), with successional stages being broad characterizations (see Figure 1). Assessment and routine monitoring of biological soil crusts may give an indication of landscape condition in a given area because crust composition tends to follow these successional pathways. Greater time

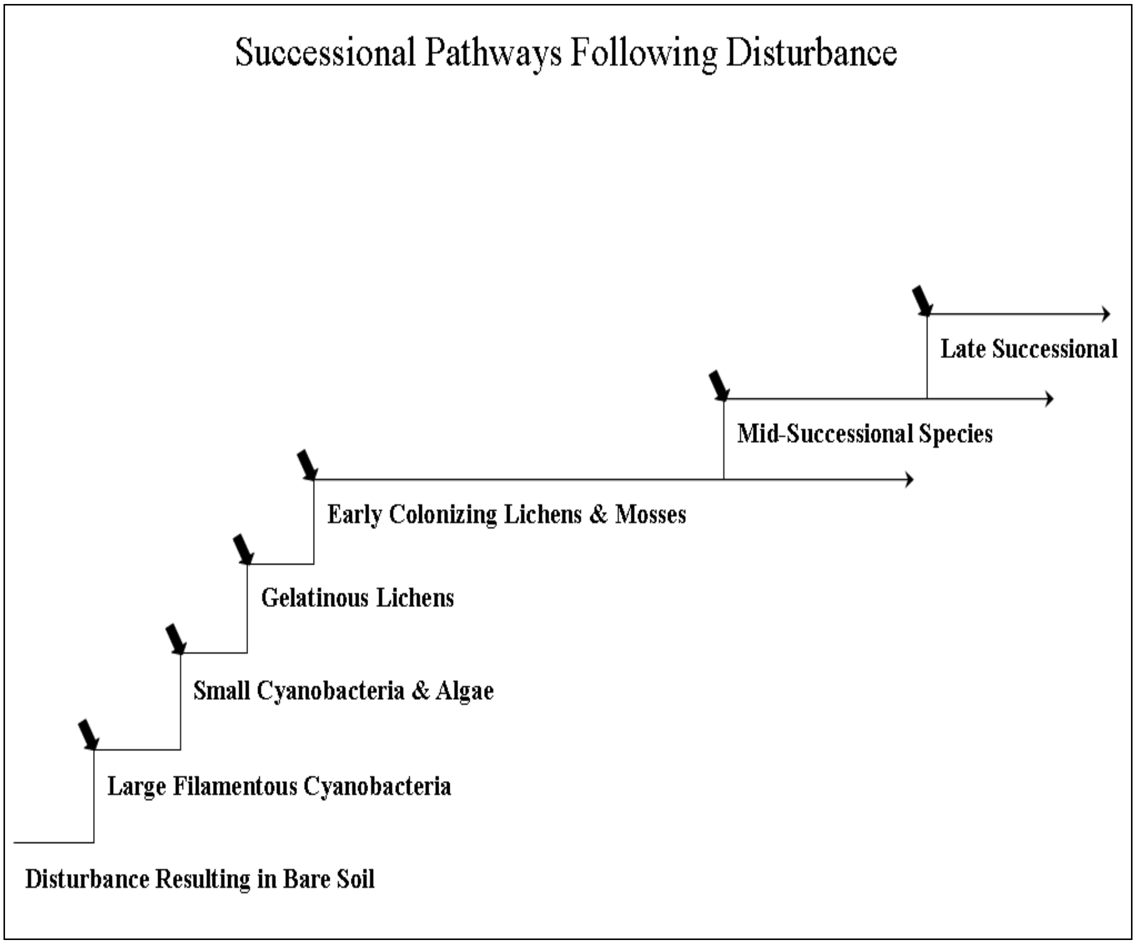

Figure 1. Biological soil crust successional processes following disturbance. Vertical arrows represent stages at which colonization of a particular group occurs. Horizontal arrows represent increased time since disturbance. Adapted from Belnap, Kaltenecker, et al. (2001).

since disturbance may relate to increased soil stability and landscape condition, as compared to less time since disturbance, decreased soil stability, and poor landscape condition. If resource managers at the YTC are interested in assessing the long-term impacts of management decisions, land use, and disturbance on the landscape, biological soil crusts should be considered. This research will provide resource managers at the YTC with baseline soil crust information, which may be useful in determining the effect of soil disturbance on overall landscape condition, and appropriate techniques for monitoring biological soil crust trends in relation to land use and management activities.

Monitoring biological soil crust composition as a component of upland ecosystems at the YTC will provide more information about the overall condition of those ecosystems in relation to military land use and may help to influence future land management decisions at the YTC. In addition, should biological soil crust monitoring at the YTC be demonstrated as useful for monitoring upland ecosystem condition in relation to military land use, then other military installations in the western United States may consider biological soil crust monitoring as a component of their upland ecosystem monitoring programs. Other federal agencies, such as the Bureau of Land Management, who manage land in arid and semiarid environments, are also interested in biological soil crust monitoring. Seeing as how these agencies deal with similar land use impacts, such as wildfire, livestock grazing, and vehicle disturbance, the results from this thesis may be useful in helping to develop biological soil crust monitoring techniques.

CHAPTER 2

LITERATURE REVIEW

Biological Soil Crusts

Belnap, Budel, and Lange (2001) give several reasons why use of the term biological soil crust is accepted: (a) in the simplest sense, this is the broadest term; (b) soil crusts are dependent upon living, biological organisms; and (c) the term lacks taxonomic implications, so cyanobacterial crusts are considered within the same realm as lichen- and moss-dominated soil crusts.

Biological Soil Crust Distribution and Composition

Biological soil crust distribution and composition can be related to several characteristics, including (a) vascular plant community relationships, (b) timing of effective precipitation, (c) landscape characteristics such as topography, (d) soil texture, and (e) chemistry.

Biological soil crusts tend to colonize bare soil interspaces of vascular plant communities. This is caused by two main factors--biological soil crust components cannot compete with vascular plants for sunlight, and organic litter buildup beneath vascular plants can bury crust components and have a negative effect on their growth (Belnap, Budel, et al., 2001; Belnap, Kaltenecker, et al., 2001). Therefore, as vascular plant cover increases, biological soil crust cover decreases and vice versa.

Harsh climatological conditions play a major role in distribution and composition of biological soil crusts. The most important environmental factor is timing and availability of moisture. Rosentreter and Belnap (2001) refer to time of year for precipitation, and potential evapotranspiration (PET) as having an influence on composition of biological soil crust. If precipitation occurs during cooler months, less is lost to evaporation, leaving more available for biological soil crust components. Within the Columbia Plain, most precipitation occurs during cooler months. Also, because PET decreases as you move northward, less moisture is lost to evaporation and soils can support crusts dominated by mosses and lichens (Rosentreter & Belnap).

In relation to aspect, soil crusts favor north- and east-facing slopes, as opposed to south- and west-facing slopes, because of a lower PET and greater available moisture (Ponzetti & McCune, 2000; Rosentreter & Belnap, 2001). Elevational relationships support the idea that, when all crust types are considered, biological soil crust cover is greater at midelevation sites as compared to low-elevation sites (Rosentreter & Belnap). Thus, crust cover will show an increase with elevation and available precipitation until vascular plants become so dense they out compete biological soil crust (Hanson, Ostler, & Hall, 1999).

Soil texture also affects composition and distribution of biological soil crusts, even though crusts are found across virtually all soil types. Biological soil crusts tend to be limited on clays with high shrink/swell ratios, as well as loose sands, while more stable silt-loams tend to support greater cover and biodiversity (Belnap, Budel, et al., 2001; Kleiner & Harper, 1977). This relationship holds true for individual crust components as well. Mosses and lichens dominate stable soils, while cyanobacteria dominate coarsely grained soils. However, after cyanobacteria stabilize soils, other components such as lichens or mosses may begin to colonize (Anderson & Rushforth, 1976).

Soil chemistry or nutrient and pH level of soil determines, to some extent, composition of soil crusts. Lichens occur across many pH levels, but phycolichens generally prefer acidic soils, whereas cyanolichens generally prefer basic soils (Jahns, 1988). Also, gypsiferous or calcareous soils support greater cover and biological diversity of biological soil crusts (Anderson & Rushforth, 1976; Belnap, Kaltenecker, et al., 2001).

Biological Soil Crust Structure

Most characteristics and factors discussed within the previous section, including geographical location and composition, determine biological soil crust structure. Structure has been classified into four distinct types: (a) smooth crusts typically dominated by cyanobacteria; (b) rugose crusts with slight microtopography made up of cyanobacteria, algae, and some lichen or moss cover; (c) pinnacled crusts characterized by frost heaving, peaked microtopography, and dominated by cyanobacteria, but with up to 40% lichen or moss cover; and (d) rolling crusts associated with higher amounts of precipitation, some frost heaving, undulating microtopography, and generally dominated by up to 80% moss and lichen cover (Belnap, Budel, et al., 2001; Belnap, Kaltenecker, et al., 2001).

Classification types are also subdivided by location in hot or cool deserts. Crust types occurring in the Columbia Plain, a cool desert, are either pinnacled or rolling. However, any of the four crust types may occur within this region or anywhere biological soil crusts colonize, as part of a successional stage and depending on local environmental factors. Following disturbance, cyanobacteria will tend to colonize a site, meaning that a smooth crust is present. This smooth crust is maintained at least until frost heaving occurs, or mosses and lichens begin to colonize the site, at which time the crust type evolves to either slightly pinnacled or rugose.

Living components of biological soil crusts include bacteria, microfungi, cyanobacteria, green algae, bryophytes (mosses and liverworts), and lichens (Belnap, Budel, et al., 2001; Belnap, Kaltenecker, et al., 2001). All of these components are taxonomically unrelated, but are very similar in terms of physiology and share adaptive traits such as the ability to dry out and terminate respiration without dying (Belnap, Kaltenecker, et al.). Biological soil crusts also have the ability to capitalize on small amounts of moisture such as dew, fog, or a very light drizzle that vascular plants may not be able to utilize (Belnap, Budel, et al., 2001). In addition, several components of biological soil crusts lack a waxy epidermal layer. Without this epidermal layer, soil crusts will leach small amounts of nutrients into the soil each time drying and wetting occurs (Belnap, Budel, et al.).

Microscopic Components of Biological Soil Crusts

Bacteria and microfungi seem to be the least studied and mentioned component of biological soil crusts; therefore, specific genera will not be discussed. Bacteria are characterized as autotrophic or synthesizing carbon from inorganic sources and heterotrophic or utilizing carbon sources that are organic (Belnap, Kaltenecker, et al., 2000). Microfungi include free-living fungi and mycorrhizal fungi. Free-living fungi are saprophytic (decomposers) and contribute living biomass to the soil (Belnap, Kaltenecker, et al.; Cooke, 1955). Mycorrhizal fungi are associated with woody or herbaceous plant roots. It is thought that many plants of the sagebrush steppe regions of the Columbia Plain, particularly species of the *Asteraceae, Poaceae,* and *Roseaceae* families, have mycorrhizal associations with their roots (Wicklow-Howard, 1994).

Cyanobacteria (previously called blue-green algae) are single-celled filamentous forms of bacteria (Prokaryotes) capable of photosynthesizing and fixing atmospheric nitrogen into a form readily available for uptake by vascular plants (Belnap, Kaltenecker, et al., 2001). Cyanobacteria are divided into two basic categories: the first is termed heterocystic, which contain cells especially for nitrogen fixation, and the second is nonheterocystic, or not able to fix nitrogen (Bothe, 1982). The most common genus of cyanobacteria on a global scale is *Microcoleus*, which occurs as bundles of filaments surrounded by a polysaccharide sheath that secrete sticky substances responsible for aggregation and eventual stability of soil particles (Belnap, Budel, et al., 2001; Belnap, Kaltenecker, et al.). It can be extremely difficult to locate cyanobacteria in the field because they appear only as a blackish covering of the soil. However, when soils contain a large amount of cyanobacteria, a surface roughening is also noticeable and detection becomes easier (Belnap, Kaltenecker, et al.).

Green algae are single-celled Eukaryotes, photosynthetic organisms. They differ from cyanobacteria in part by not fixing nitrogen and often appearing greenish in color (Johansen et al., 1993). Green algae are also very difficult to locate in the field because of their microscopic size and colony formation beneath the soil surface. Soil algae are difficult to observe without a microscope, but a trained eye may be able to observe them as a greenish tinge to the soil when moist (Belnap, Kaltenecker, et al., 2001).

Macroscopic Components of Biological Soil Crusts

Mosses and liverworts represent bryophytes, or tiny nonvascular plants that reproduce via spore production. Within arid environments, mosses will sometimes lack reproductive structures, and will reproduce asexually by fragmentation (Belnap, Kaltenecker, et al., 2001; McIntosh, 1986). Mosses and liverworts tend to occur most often within more moist semiarid environments, such as the Northern Great Basin and the Columbia Plain (Rosentreter & Belnap, 2001). The most common mosses of the Columbia Plain are represented by *Tortula*, *Bryum*, and *Ceratodon*, while the most common liverwort is *Cephaloziella divaricata* (Kaltenecker & Wicklow-Howard, 1994; Ponzetti & McCune, 2000). Bryophytes also play a major role in soil aggregation and stabilization, and can trap wind-blown soil particles in their leaves. Structural components of mosses and liverworts include a rhizoid, or root-like structure, firmly attaching plant to soil (Sanders, 1994).

The last macroscopic component of biological soil crusts is characterized by a symbiotic relationship between a fungus and either cyanobacteria or algae (Ahmadjian & Hale, 1974). This relationship, or symbiosis, is referred to as a lichen. Lichens are often organized into two main functional categories, phycolichens or those with green algal photobionts, and cyanolichens or those with cyanobacterial photobionts (Jahns, 1988). A photobiont is an organism relied upon by the fungus as a photosynthetic energy source. Lichens can be further subdivided into several morphological groups: crustose, gelatinous, squamulose, foliose, and fruticose. Within the Columbia Plain, crustose lichens are characterized by the genus *Diploschistes*, *Collema* and *Leptogium* characterize gelatinous lichens, *Endocarpon* and *Psora* characterize squamulose lichens, *Peltigera* characterizes foliose lichens, and *Cladonia* characterizes fruticose lichens (Belnap, Kaltenecker, et al., 2001; Ponzetti & McCune, 2000; Rosentreter & Belnap, 2001).

Like all previously mentioned crust components, lichens also have structures capable of soil aggregation and stability enhancement. These structures are called rhizomorphs, which extend from the lower portion of the lichen, are covered by a dense layer of hyphae (fungal material), and bind soil particles, leading to increased soil stability (Sanders, 1994).

Biological Soil Crust Function

The various functions or ecological roles of biological soil crusts include, but are not limited to (a) contributions to nitrogen and carbon cycles, (b) thermal relations, (c) vascular plant relations, (d) influence on the hydrologic cycle, and (e) soil stabilization.

Nitrogen Cycle

Cool deserts generally support very few nitrogen-fixing plants and are thought to be relatively limited in amount of available nitrogen (Farnsworth, Romney, & Wallace, 1976). Nitrogen fixation by cyanobacteria and cyanolichens is an important contribution to arid ecosystems because biological soil crust components make up for a lack of nitrogen fixing vascular plants (Evans & Ehrlenger, 1993). Biological soil crusts are often dominated by nitrogen-fixing cyanobacteria and cyanolichens in the western United

States, and these organisms provide ample nitrogen contributions through day and night fixation (Belnap, Kaltenecker, et al., 2001).

Nitrogen amounts fixed by biological soil crusts vary greatly, especially depending on moisture, temperature, and available light. In fact, available moisture is considered to be the dominant factor, followed by temperature and light (Belnap, 2001). For sagebrush steppe regions of central Washington, biological soil crust nitrogen-fixation may be more prevalent in the system as compared to other arid and semiarid regions where biological soil crusts occur, because moisture is readily available and PET is generally lower. However, should environmental conditions be poor, available moisture, light, and moderate temperatures may not matter. For example, evidence suggests that reduced nitrogen inputs occur following grazing and other mechanical disturbances (Evans & Belnap, 1999).

Carbon Cycles

Semiarid and arid environments are known to experience low moisture levels and low vascular plant productivity. Lower productivity results in less organic carbon for the system. Biological soil crust productivity, however, is relatively high in these systems, providing a significant source of fixed carbon to the system (Beymer & Klopatek, 1991). This input of carbon is extremely important as an energy source for soil microbial populations (Belnap, Kaltenecker, et al., 2001).

Carbon fixation is also dependent upon environmental factors. For example, photosynthesis occurs with relatively low moisture amounts and moderate temperatures, and increases with greater moisture and higher temperatures. However, above 28 °C rates decline rapidly (Lange, 2001). High soil temperatures decrease respiration in crustal organisms, so soil crusts in summer-rain deserts may be less likely to capitalize on moisture and begin respiration as compared to those of winter-rain deserts where temperatures are cooler when precipitation occurs (Lange). Semiarid portions of the Columbia Plain receiving winter precipitation provide moisture easily utilized by biological soil crusts.

Thermal Relations

Presence or absence of biological soil crusts covering desert soils has an influence on soil surface temperature in terms of albedo, or measure of energy reflected off soil surfaces (Belnap, Kaltenecker, et al., 2001). Well-developed biological soil crusts provide a darker soil surface, absorbing sunlight and raising soil temperature. Absence of biological soil crust has the opposite effect. Lower temperatures have a negative impact on microbial activity, vascular plant photosynthesis, nutrient uptake, seed germination, and seedling growth rates (Bush & Van Auken, 1991).

Effects on Vascular Plants

Relationships between biological soil crusts and vascular plants can be beneficial for the latter in a number of ways, including (a) seed germination and establishment, (b) seedling survival, and (c) plant nutrition. Cool deserts are characterized by lichen- and moss-dominated crusts with frost-heaved soils and greater accumulations of organic matter, which create fertile microsites (Rosentreter & Belnap, 2001). These fertile microsites are suitable for entrapment, germination, and establishment of vascular plant seeds. Studies provide contrasting evidence suggesting that seed germination of native perennials is either enhanced or not affected by presence of biological soil crust. Vascular plant adaptations of hygroscopic or hygrochasic awns (self-burial mechanisms) may aid in seed germination (Belnap, Prasse, & Harper, 2001). Biological soil crusts may provide a barrier to germination and establishment of exotic annuals including *Bromus tectorum* and *Salsola kali*, because these species lack awns for self-burial (Evans & Young, 1984; Kaltenecker, Wicklow-Howard, & Pellant, 1999).

Seedling survival was also assessed in various studies with mixed results. All studies have shown that presence of biological soil crust either has neutral or positive effects on vascular plant establishment (Belnap, Prasse, et al., 2001; Harper & St. Clair, 1985; St. Clair et al., 1984). More detailed studies should be performed in order to establish a firm relationship between crust components and survival of vascular plant seedlings. Vascular plant nutrition seems to be positively enhanced by presence of biological soil crust in all cases. An increased amount of nitrogen is most significant, but uptake of other nutrients such as magnesium, potassium, and zinc has also been observed (Harper & Belnap, 2001).

Hydrologic Roles

Specific roles played by crust components in the hydrologic cycle are fairly well observed. Biological soil crusts in general and several individual species have considerable moisture holding capacity. For example, cyanobacteria and gelatinous lichens have the ability to absorb and hold up to 10 times their original volume in water (Belnap, Kaltenecker, et al., 2001; Campbell, 1977). Also, it has been repeatedly observed that moss and lichen crusts of cool deserts hold moisture at the soil surface much longer than adjacent uncrusted soils (Harper & Marble, 1988; Warren, 2001). This additional moisture may have an influence on vascular plant seed germination and microbial populations.

Biological soil crusts also have an influence on water infiltration and runoff, thus having an impact on landscape hydrology. Several studies discussed by Belnap and Eldridge (2001) show greater infiltration rates for moss- and lichen-dominated crusts compared to lichen and cyanobacteria crusts. Within cool deserts, where frost heaving occurs, microtopography leads to pooling of water and higher infiltration rates (Belnap, Kaltenecker, et al., 2001; Loope & Gifford, 1972).

Infiltration rates will tend to vary by soil texture type. Soils with coarse texture, such as sand, have high infiltration rates, while fine textured clays have low infiltration rates. Fine textured silt-loams with good aggregation have improved infiltration (Belnap & Eldridge, 2001; Belnap, Kaltenecker, et al., 2001). Soil crusts are known to improve aggregation of soil particles, thus enhancing infiltration rates.

Soil Stabilization

Biological soil crusts are known to enhance soil stability for a variety of reasons. Cyanobacteria polysaccharide sheaths and moss and lichen rooting structures help to bind or aggregate soil particles (Belnap, Prasse, et al., 2001; Campbell et al., 1989). In addition, biological soil crusts provide a surface microtopography, because of two-dimensional and three-dimensional growth structures, that helps to protect against raindrop impact, surface water runoff, and wind (Belnap, Prasse, et al.; Campbell et al.;

Harper & St. Clair, 1985). These characteristics of biological soil crusts help to protect soil against wind and water erosion in arid and semiarid environments.

Biological Soil Crusts of the Columbia River Region

Using all that has been discussed to this point, the following is a general synthesis regarding composition, structure, and distribution of biological soil crusts in central Washington: (a) due to the northern location and available moisture, moss and lichen dominated crusts will be more prevalent here; (b) these crusts will include representatives of all components; (c) the classification of these crusts will tend to be either pinnacled or rolling, with the latter being more common; and (d) greater crust cover will occur on north- and east-facing slopes at midelevations with stable, silt-loam or calcareous soils assuming that disturbance is minimal or absent. These assumptions will help to guide analysis of biological soil crust cover at the YTC in relation to environmental variables.

Even though moss and lichen crusts tend to dominate landscapes in the Columbia River region, successional patterns following disturbance will play a major role. In most cases cyanobacteria and algae will colonize a site, followed by colonizing lichens and mosses, early successional mosses and lichens, and finally late successional mosses and lichens (Figure 1; Belnap, Budel, et al., 2001; Belnap, Kaltenecker, et al., 2001). This relationship can also be seen in the morphological groups discussed below.

Studies conducted to date on biological soil crusts specific to the Columbia River region occurred in southern Idaho (Kaltenecker & Wicklow-Howard, 1994), Horse Heaven Hills in central Washington (Ponzetti & McCune, 2000), and at the Hanford Reach National Monument in central Washington (McIntosh, 2003). When comparing the list of lichens and bryophytes observed between the three studies, a total of 29 species were common to all three study sites (see Table 1). Fourteen additional species were common only to Horse Heaven Hills and Hanford National Monument. Ten additional species were common only to southern Idaho and Horse Heaven Hills. Two additional species were common only to southern Idaho and Hanford National Monument. On the other hand, 29 species, a mix of lichens and mosses, were unique to southern Idaho, 58 species, mostly lichens, were unique to the Horse Heaven Hills, and 23 species, mostly mosses, were unique to the Hanford National Monument. This could possibly lead to the assumption that crusts from the three different subregions of the Columbia Plain are

Table 1

Lichen and Bryophyte Diversity at Three Study Sites of the Columbia Plain

Lichens and bryophytes	Number of species
Total species at southern Idaho	74
Total species at Horse Heaven Hills	109
Total species at Hanford Reach National Monument	81
Common to southern Idaho, Horse Heaven Hills, and Hanford Reach National Monument	29
Common only to Horse Heaven Hills and Hanford Reach National Monument	14
Common only to Horse Heaven Hills and southern Idaho	10
Common only to Hanford Reach National Monument and southern Idaho	2
Unique to southern Idaho	29
Unique to Horse Heaven Hills	58
Unique to Hanford Reach National Monument	23

considerably different. However, given that a great number of species were common to all three sites and that biological soil crust composition is tied so closely to environmental conditions such as slope, aspect, soil texture, soil chemistry, disturbance history, and vascular plant community, a determination could be made that these sites are relatively similar. In addition, a moss expert performed the study at Hanford National Monument (McIntosh) and lichen experts performed the study at Horse Heaven Hills (Ponzetti & McCune), which might be part of the reason behind the number of unique species at these two sites.

Biological Soil Crust Management and Monitoring

Management emphasis for biological soil crust has focused primarily on how to limit disturbance and how to determine the most ecologically sound methods for enhancing recovery of native plant communities following disturbance. Disturbances are generally broken down into three main categories that include, fire, livestock grazing, and human/recreational disturbances. Fire disturbance includes wildfire and prescribed fire used for reducing fuel loads and enhancing native plant communities. Livestock grazing usually refers to sheep and cattle grazing allotments on public land. Human and recreational disturbances might include military training in the case of the YTC, off-road vehicle use, mountain biking, and hiking.

Management of biological soil crusts also includes monitoring condition and long-term trends in relationship to those disturbances mentioned above. Monitoring methods include the use of total crust cover and broad categories often referred to as morphological groups (Belnap, Kaltenecker, et al., 2001).

Total Lichen/Moss Cover

Total lichen and moss cover, hereafter referred to as total crust cover, has been utilized by natural resource managers at the YTC as a variable for monitoring trends in biological soil crust over time. LCTA and several other monitoring protocols used at the YTC for assessing long-term trends in natural resources and restoration activities have often included biological soil crust as a component of ground cover measurements. Total crust cover is the only variable measured to assess the condition and trend of biological soil crusts at the YTC as part of these protocols (Bern, 1996a; ENRD, 2001).

Biological Soil Crust Morphological Groups

If biological soil crusts are to be considered by managers in a given area, then baseline information needs to be acquired through soil crust surveying and monitoring. One problem, identified by scientists and resource managers, is that biological soil crusts are seldom included as part of routine landscape condition assessments (Eldridge & Rosentreter, 1999; Ponzetti et al., 1998; Rosentreter, Eldridge, & Kaltenecker, 2001). Several studies, such as one completed by Eldridge and Rosentreter, have explored different techniques for assessing biological soil crust condition.

Morphological group characterizations (see Table 2) have been identified as a useful technique for assessing soil crust condition on a landscape level (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999; Kaltenecker, 1997). Morphological groups are broad characterizations of crust components that can be relatively easily identified during fieldwork (Eldridge & Rosentreter; Kaltenecker; Ponzetti et al., 1998). Morphological group characterizations were first developed for use with lichens in forested

Table 2

Morphological Group Characterizations

Morphological group	Description	Genera
Cyanobacteria	Blue-green or blackish, thread-like strands	*Microcoleus, Nostoc*
Gelatinous lichen	Turning jelly-like when wet, blackish in color	*Collema, Leptogium*
Crustose lichen	Crust-like growth form tightly attached to substrate	*Diploschistes*
Squamulose lichen	Lichens with discrete scales, warts, or flakes	*Peltula, Psora*
Fruticose/foliose lichen	Three-dimensional, leafy or shrubby growth	*Peltigera, Cladonia*
Short mosses	Short growing nonvascular plants green and erect	*Bryum, Ceratodon*
Tall mosses	Tall growing nonvascular plants green and erect	*Tortula*
Liverworts	Prostrate, green, leafy plants	*Riccia, Cephaloziella*

Note. Adapted from Eldridge and Rosentreter (1999).

environments (Rosentreter, 1996). They have since been broadened to include components other than lichens and have been applied to biological soil crusts on a limited basis in Australia and western North America (Eldridge & Rosentreter; Ponzetti et al.).

Justification for the use of morphological groups goes beyond the ease of identification and relatively rapid field assessment. Eldridge and Rosentreter (1999) suggest that different morphological groups can be indicators of water and wind erosion control, soil moisture, landscape stability, and soil crust disturbance recoverability because of varying susceptibility to disturbance and relative ability to colonize a site following disturbance (see Figures 2 and 3). Therefore, differences in soil crust components (i.e., cyanobacteria vs. lichens vs. mosses) and differences among component groups (i.e., tall moss vs. short moss, or crustose lichen vs. gelatinous lichen) may provide information about soil and landscape condition in relation to disturbance (Eldridge & Rosentreter; Ponzetti et al., 1998).

Because morphological groups are easily identified, provide for rapid field assessment, and can be used as indicators of numerous ecosystem functions, this technique may be useful for assessing and monitoring biological soil crust condition over time. However, Ponzetti et al. (1998) caution that use of morphological groups will require adequate training in identifying and distinguishing between the different groups

Increasing Morphological Complexity>>	**3-dimensional lichens**	Very high	Very high	High
	Bryophytes & 2-dimensional lichens	High	Moderate	Moderate
	Cyanobacteria	Low	Low	Low
		Asexual reproduction	**Sexual reproduction**	**Asexual & sexual reproduction**
	Relative Diversity of Reproductive Strategies >>			

Figure 2. Susceptibility of morphological groups to disturbance. Adapted from Eldridge and Rosentreter (1999).

Increasing Morphological Complexity>>	**3-dimensional lichens**	Very slow	Slow	Slow
	Bryophytes & 2-dimensional lichens	Moderate	Fast	Moderate to fast
	Cyanobacteria	Very rapid	Very rapid	Very rapid
		Asexual reproduction	**Sexual reproduction**	**Asexual & sexual reproduction**
	Relative Diversity of Reproductive Strategies >>			

Figure 3. Ability of morphological groups to recolonize a site following disturbance. Very rapid < 6 months; fast = 6 to12 months; moderate = 1 to 5 years; slow = 5 to 10 years; and very slow > 10 years. Adapted from Eldridge and Rosentreter (1999).

while conducting fieldwork. Another caution (J. Ponzetti, personal communication, April 5, 2003) is that the information provided in Figures 2 and 3 is theoretical, and may not apply in all situations.

Biological Soil Crust Dimensionality Groups

Biological soil crust components are known to improve soil stability through protection from the forces of nature such as wind and water. According to Rosentreter and Eldridge (2004), the influence on soil stability may be directly related to an organism’s dimensionality (i.e., its vertical and horizontal structure). Soil crust components can be divided into three different groups, which are either one dimensional, two dimensional, or three dimensional. Algae, cyanobacteria, and liverworts make up the one-dimensional group, crustose and squamulose lichens make up the two-dimensional group, and short moss, tall moss, foliose and fruticose lichens make up the three-dimensional group.

One-dimensional components of biological soil crust occur within the first few millimeters of soil, and provide some protection from water and wind erosion by beginning to bind soil particles (Rosentreter & Eldridge, 2004). Two-dimensional components are generally much larger and grow on top of the soil surface, thus providing greater resistance to erosional forces (Rosentreter & Eldridge). Three-dimensional components provide even greater resistance to erosional forces and trap sediments more easily (Rosentreter & Eldridge). Proportions of these three different groups may be easier and more rapidly collected than morphological groups along LCTA transects, while providing useful information as to a site's ability to resist wind and water erosion.

Rosentreter and Eldridge (2004) used this method to compute the Biological Soil Crust Stability Index (hereafter referred to as dimensionality index), and have found it to be useful in showing strong relationships with rangeland health indicators. This method is still being tested and revised.

Biological Soil Crust Sampling Techniques

Biological soil crust sampling techniques along transects are basically divided into two main categories: line intercept and quadrat sampling. Line intercept techniques encompass the point-line intercept sampling technique. These techniques use 10-m or 20-m transects and the proportion of biological soil crust species or groups are recorded along those transect (Belnap, Kaltenecker, et al., 2001; Canfield, 1944; Kaltenecker, 1997). The line intercept sampling technique records the proportion of each group or species that the transect line intercepts, or crosses. Point-line intercept sampling technique records proportion of each group or species at predetermined, dimensionless points along the line. Quadrat sampling, on the other hand, consists of rectangular or square frames being placed randomly along a transect or across the landscape. Percentage of cover of each biological soil crust species or group is then estimated within the confines of each frame (Belnap, Kaltenecker, et al.).

Line intercept methods appear to be more suitable than the use of quadrat sampling for monitoring long-term trends of biological soil crust at the YTC, for the following reasons. Line intercept is a reliable and quick method for sampling patterned landscapes (i.e., patterns of vascular plant cover and bare soil interspaces) such as appears in arid and semiarid ecosystems, and thus is more repeatable with different observers over long periods of time (Belnap, Kaltenecker, et al., 2001; Kaltenecker, 1997). In addition, Rosentreter and Eldridge (2004) found the line intercept method along 20-m transects to be useful in determining the dimensionality index, mentioned previously, across patterned vegetation communities in Idaho and western Australia.

The basic difference between the two line intercept methods used for this thesis, line intercept and point-line intercept, is that species or groups are recorded at pre-determined points along a line for point-line intercept, whereas species or groups are recorded every centimeter for line intercept (Belnap, Kaltenecker, et al., 2001; Rosentreter et al., 2001). Line intercept, as opposed to point-line intercept, appears to be more desirable for LCTA plots at the YTC because of several reasons. First, during the 2003 field season, a pilot study was completed by Colorado State University and

CEMML using biological soil crust morphological groups and the point-line intercept method. This study utilized a sample of the LCTA plots and recorded points at every meter along the 100-m transects. Along with morphological groups, bare ground, litter, rock, and vegetation were also recorded. Jones and Kunze (2003) found that 100 points across 100 m were not adequate for representing the variation in biological soil crust morphological groups on the YTC. It was suggested that 200 or more points across 100 m might accurately describe the variation, but additional sampling time was undesirable. Therefore, point-line intercept sampling along LCTA transects for this thesis represented twice that amount. A 20-m segment of each transect was utilized for sampling, meaning that 40 ground-cover intercepts were recorded. If applied to 100 m, then 200 ground-cover intercepts would be recorded. Twenty meters was also recommended by Rosentreter and Eldridge (2004) as an appropriate distance for implementing dimensionality sampling along a line transect. For line intercept, every centimeter of the 20-m length was characterized, resulting in the equivalent of 2,000 intercepts. The 20-m stretch was utilized for recording results of both techniques along each of the transects measured in this study.

Line intercept, using a 20-m section of each 100-m transect, may be just as rapid as point-line intercept, but may also accurately describe the variation in biological soil crust at each site as well as provide proportion of morphological groups along each line. An additional benefit of this sampling technique is that Rosentreter and Eldridge's (2004) dimensionality index may be recorded simultaneously, giving additional information as to trends in soil stability and erosion control. Because some overlap and discrepancy exists between these two types of line intercept techniques for biological soil crust data collection, it was decided that testing different methods and techniques against one another would be most beneficial for determining the most appropriate methodology for adding to RTLA monitoring at the YTC.

CHAPTER 3

STUDY AREA

Location

The YTC is located in south central Washington (see Figure 4) within the Columbia Plain, at approximately 120°, 27' West and 46°, 40' North. The YTC is bounded by the Columbia River to the east, Interstate 90 to the north, Interstate 82 to the west, and extends just beyond Yakima Ridge to the south. This area measures approximately 327,242 acres in size (ENRD, 2001).

Geology

A series of basalt flows, known as the Columbia River Basalt Group, occurring in the middle Miocene followed by late Tertiary folding and faulting, are mostly responsible for molding the current landscape of the Columbia Plain (Orr & Orr, 1996; Reidel & Campbell, 1989). The YTC landscape is primarily composed of folded and faulted basalt flows interbedded with sedimentary deposits (Reidel & Campbell; Salstrom & Easterly, 1998). Glacial lake Missoula flood deposits were also partially responsible for shaping the eastern boundary of the YTC along the Columbia River (Bjornstad, Fecht, & Pluhar, 2001).

Topography

Topography characteristic of the Columbia Plain varies from steep escarpments and deep canyons to low, rolling plains (U.S. Department of the Army, 1989). Elevations range from close to 500 ft above sea level at the banks of the Columbia River near Priest Rapids Dam to an elevation of 4,191 ft on top of Yakima Ridge in the southeast portion

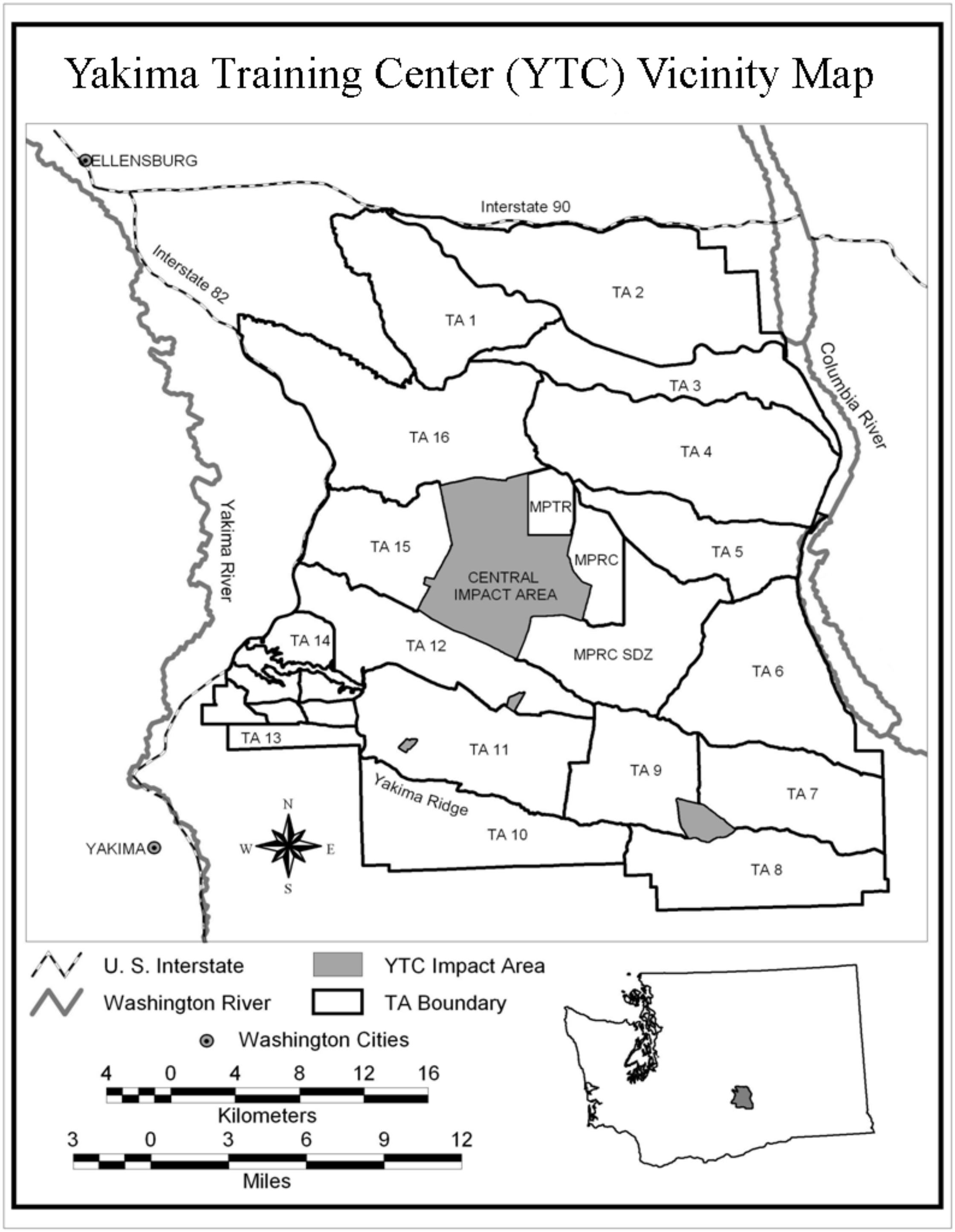

Figure 4. Location of the Yakima Training Center. TA = training area.

of the YTC (U.S. Department of Defense, 1990). Five east-to-west-trending ridges occupy the installation and include from south to north, Yakima Ridge, Umtanum Ridge, Manastash Ridge, the Saddle Mountains, and the Boylston Mountains. These ridges generally average elevations from 3,000 to 4,000 ft.

Soils

Soils of the YTC have formed on a variety of parent materials including loess, Missoula floodwater outwash, residuum, alluvium, and colluvium, and are mostly shallow, light, silty loams characteristic of arid and semiarid environments (Soil Conservation Service [SCS], 1989). These soils are largely undeveloped due to several factors, including low precipitation, lack of weathering, stripping by late Pleistocene (Missoula) flood episodes, and wind erosion (Busacca & McDonald, 1994; SCS). A majority of the soil types found on the YTC are Mollisols and Aridisols, with several suborders of the Entisols and Alfisols (Natural Resources Conservation Service, 2005). Also present are soils found on windswept ridges and south-facing slopes that tend to be shallow and rocky (SCS). Loamy and cobbly loam soil types dominate the deeper soils of the YTC, and are most commonly associated with the dominant vegetation type *Artemisia tridentata/Pseudoroegneria spicata*.

Climate

Climate of the YTC, predominantly influenced by air masses following the path of westerly winds and controlled by the rain shadow of the Cascade Mountains, is typical for the central Washington area of the Columbia Plain and would be considered a cool desert (Bruce, Creighton, Emerson, & Morgan, 2001; Daubenmire, 1970; Grant County

Public Utility District, 1991; Sullivan, 1994). Climatic characteristics of the Columbia Plain are moderately cold and snowy winters; wet springs; hot, dry summers; and warm, relatively dry autumns (Meinig, 1968). A majority of the precipitation in the region occurs during winter and early spring, usually in the form of snow at higher elevations (National Climatic Data Center [NCDC], 2005). Weather station data collected at the YTC from 1984 to 2000 show an annual average of 7.5 in. with a majority of accumulation coming from October through May (ENRD, 2001). Mean monthly precipitation for Yakima shows a majority of precipitation occurring between November and May (see Figure 5). Mean daily temperature averaged between 25 and 35 °F during

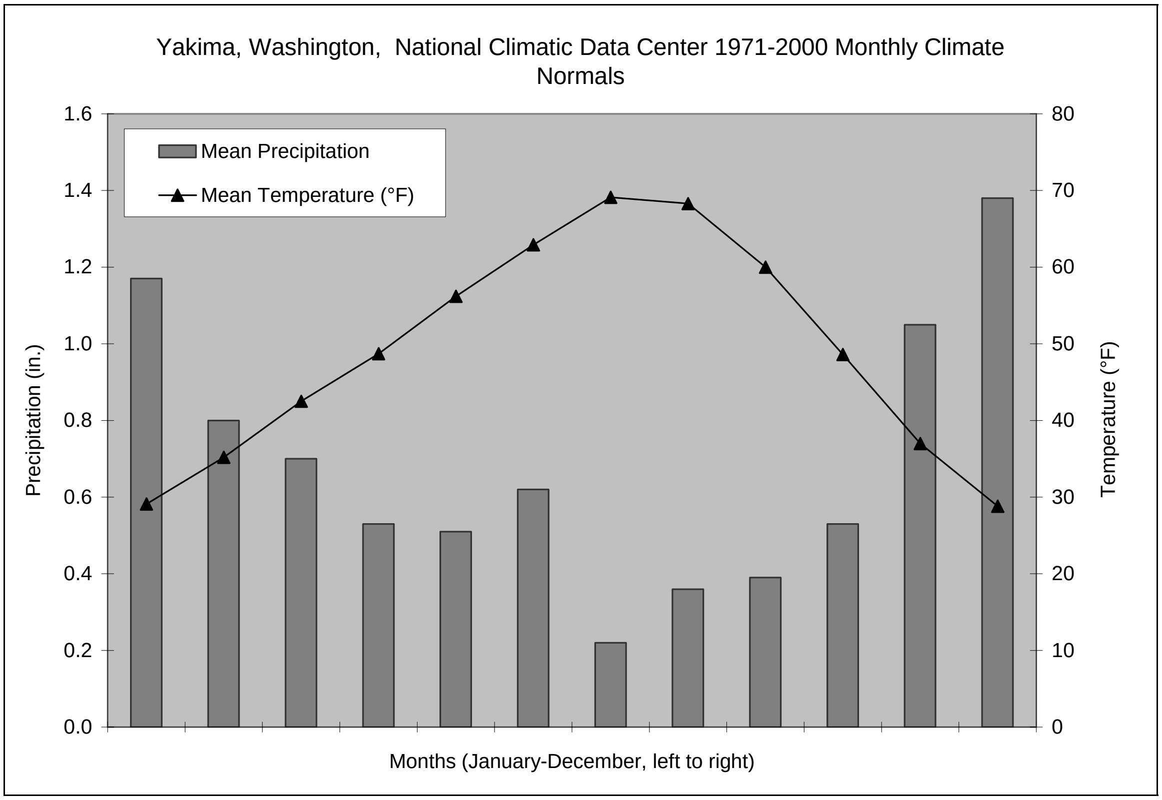

Figure 5. Mean monthly temperature and precipitation for Yakima, Washington 1971-2000 (NCDC, 2005).

winter months and between 60 and 70 °F during summer months from 1971 to 2000 (Figure 5) (NCDC, 2005).

Vegetation

The YTC is located within the shrub-steppe vegetation province of Franklin and Dyrness (1973). The area is within the *Artemisia tridentata/Pseudoroegneria spicata* zone of the Columbia Plain (Daubenmire, 1970). A majority of the training center is dominated by the big sagebrush (*Artemisia tridentata*) and bluebunch wheatgrass (*Pseudoroegneria spicata*) vegetation type, which generally coincides with loamy or cobbly loam soil types (Bern, 1996a; Salstrom & Easterly, 2000; SCS, 1989). The second most dominant vegetation type, corresponding with shallow, rocky soils or lithosols, is the stiff sagebrush (*Artemisia rigida*) and native bluegrass (*Poa secunda*) vegetation community (ENRD, 2001).

Sagebrush and bunchgrass community types found across the YTC are further broken down into three habitat types, for ease of LCTA data comparisons (Jones & Kunze, 2003). Sagebrush and native bunchgrass community types are grouped together into the shrub-steppe habitat types. Shallow, rocky soils tend to be dominated by the stiff sagebrush (*Artemisia rigida*) and Sandberg's bluegrass (*Poa secunda*) vegetation type (Salstrom & Easterly, 2000; SCS, 1989). Vegetation communities occurring on shallow soils are lumped together as dwarf shrub-steppe habitat types (Jones & Kunze). Also, shrub-steppe habitat types disturbed by fire or military training, resulting in conversion to grassland, are lumped together as grass-steppe habitat types (Jones & Kunze).

Historical Land Use

Evidence of indigenous peoples in the region dates back 10,000 to 11,000 years before present (Bruce et al., 2001; Hunn, 1990; Sullivan, 1994). These people evolved without Eurasian influence until indirect impacts related to the 17th-century Spanish colonization, followed by the Lewis and Clark expedition, who first made contact with groups in the area, in approximately 1805 (Bruce et al.; Hunn). Trading companies, such as the Pacific Fur Company, had the next major influence around 1811, which may have impacted Columbia River tributaries within the YTC and established posts from Astoria, Oregon to Okanogan, Washington (Bruce et al.; Hunn).

Settling and homesteading of the Columbia Plain occurred during the late 1840s and early 1850s, with extreme impacts from overgrazing of sheep and cattle between the late 1800s and early 1900s (Hunn, 1990; Kaltenecker, 1997; Sullivan, 1994). Use of the land prior to military occupation was dominated by small homesteads and domestic animal grazing, which is evidenced by the large amounts of abandoned range and homestead developments, including farmed areas, corrals, fences, sheds, barns, houses, and a failed dam along Selah Creek.

The U.S. Army acquired land in the region during 1941 and established a 24,300-ha antiaircraft artillery range in 1942 (Bern, 1996a). The YTC, as a subinstallation of Fort Lewis, Washington, serves the needs of the U.S. Army, U.S. Navy, U.S. Air Force, U.S. Marines, and North American Trade Organization, including British, Canadian, and Japanese forces (Bern, 1996a). Military training has resulted in disturbances such as wildfires and off-road vehicle use that have led to changes in vascular plant communities and increased soil erosion and compaction.

It is important to note that throughout this region, humans have been present and actively manipulating resources for thousands of years, with more detrimental impacts occurring over the last 200 years. It is reasonable to consider that biological soil crusts have evolved along with all of the human land use impacts discussed above. However, the condition of biological soil crusts has most likely been altered significantly by the increasingly intensive uses occurring over the past 200 years. More specific impacts of livestock grazing, military training, and fire will be discussed below.

Integrated Training Area Management

Implementation of the LCTA is directly related to the mission and purpose of the YTC, which is to provide Fort Lewis and the U.S. Army with opportunities for realistic training. As a training facility, the YTC must comply with the U.S. Army's Integrated Training Area Management Program (ITAM), which was established to guide army training and environmental stewardship under Army Regulation 350-4 (U.S. Army Environmental Center [USAEC], 1999a).

History and Development of Integrated Training Area Management and Land Condition-Trend Analysis

The U.S. Army is charged with being capable of deploying a "total force effort" or forces powerful enough to defeat any potential enemy (USAEC, 1999a). This requires that the army must train to deploy rapidly, fight effectively, be self-sustaining, win quickly, and stay in power, all while limiting casualties. Therefore, training efforts must be performed using “real world” examples and experiences, and must occur on lands controlled by the federal government. Inevitably, landscape damage will be a result of this training. However, the army is a federal entity, thus it is subject to federal laws requiring environmental stewardship.

Environmental stewardship is a term that the army defines as “the management and administration of the environment” (USAEC, 1999a). Essentially, the above-mentioned statement means that the army knows about environmental impacts caused by training and that federal laws require minimization of those impacts. In fact, the National Environmental Policy Act (1970) and U.S. Army Regulation 200-2 (U.S. Department of the Army, 1980) require that the army minimize or avoid short- and long-term impacts on military lands (USAEC, 1999b).

In 1984, faced with political and environmental pressure, the army hired a panel of scientists to assess resource conditions of army installations and training areas (USAEC, 1999b). Problems outlined by this panel of scientists were that army lands experience excessive soil erosion and natural resources were subordinate to the training mission. These findings led the army to require of the U.S Army Construction Engineering Research Laboratory development and implementation of ITAM, which included such components as LCTA. Essentially, ITAM was designed to perform two tasks: develop and maintain resource management plans, and complete adequate resource inventories on all military installations (USAEC, 1999b).

The LCTA component of ITAM was first implemented as a pilot project at Fort Carson, Colorado and Fort Hood, Texas in 1985, and was considered successful. ITAM was then required by the secretary of the army to be implemented on all installations and training areas as of 1987 (USAEC, 1999b). During the 1989 field season, ITAM and LCTA were fully implemented at the YTC.

Originally, LCTA included 202 core-sampling plots, because the YTC was considerably smaller prior to 1994. Sixty core plots were added in 1994, in order to monitor military training activities on the recently acquired Northern Expansion Area.

Land Condition-Trend Analysis

LCTA is a monitoring program designed to assess the short- and long-term impacts of military training activities on army training lands. One hundred-meter transects were established across the landscape, in order to represent the major vegetation and soil types. Variables of interest along each transect include (a) vascular plant composition, cover, and height using nested frequency, belt transect, and visual obstruction measurements; (b) ground cover including litter, rock, bare ground, and cryptogams using point-line intercept measurements; (c) soil characteristics using a qualitative checklist; and (d) observable training disturbance. These transects are then reevaluated every 5 years and assessed for a trend, or pattern in military training activities and disturbances.

Since its implementation in 1989 and the addition of Northern Expansion Area plots, LCTA was constantly reevaluated and altered to better fit the training mission at the YTC. Changes to the ITAM program and LCTA have included the addition of plots for monitoring revegetation and restoration projects, as well as plots designed to monitor impacts on sensitive wildlife habitats. The U.S. Army and the YTC will continue to evaluate the effectiveness of ITAM and LCTA for assessing military training impacts, especially in regard to the army's mission of preparedness for national defense.

Recent changes in the ITAM program have resulted in a transformation from the long-term ecosystem monitoring plots used in LCTA to the new RTLA guidelines that stress assessing specific impacts of military training and suggest qualitative approaches to monitor for those impacts whenever possible. The YTC is currently developing a protocol following RTLA guidance.

Effects of Disturbance at the Yakima Training Center

Since acquisition of the YTC in 1942, disturbances to biological soil crust have largely been related to livestock grazing, military training, and fire. Livestock grazing was removed following the completion of the 1990 to 1995 grazing leases. Therefore, the most recent disturbances on the YTC are related to military training. Disturbances to biological soil crusts result in reduced cover and diversity, which can increase soil erosion, diminish water infiltration, and negatively impact nutrient and mineral cycles (Belnap & Eldridge, 2001).

Livestock Grazing

Livestock grazing can heavily impact and destroy biological soil crust because of the trampling action of grazing animals' hooves (Warren & Eldridge, 2001). Anderson, Harper, and Holmgren (1982) found that both total cryptogamic cover and species diversity significantly declined under grazing pressure. Other studies discovered similar results suggesting that biological soil crust cover, diversity, and frequency all decreased in areas with consistent grazing pressure (Brotherson, Rushforth, & Johansen, 1983;

Evans & Belnap, 1999). The secondary impacts of livestock grazing are similar to fire and military training, in that biological soil crusts have reduced capabilities to perform ecosystem functions such as protect soil from erosional forces and influence water, mineral, and nutrient cycles.

Recorded history of livestock grazing within the confines of the YTC is limited to the period 1960 to 1995. However, livestock grazing is known to have occurred across a large portion of the installation dating back into the middle to late 1800s (Bruce et al., 2001). During the period 1960 to 1995, livestock grazing was managed on a renewable 5-year lease program. The final livestock-grazing lease period, 1990 to 1995, consisted of 6 grazing units over a relatively small portion of the installation in comparison to years prior (see Figure 6). Very little data are currently available for the Northern Expansion Area, which was acquired in 1994, except that estimated grazing utilization was heavy.

Upon review of animal unit months (AUMs) for each grazing unit during each lease period, some interesting trends in the management of livestock grazing were discovered. First, AUMs across all grazing units peaked in the early 1970s, only to drop off drastically in the mid-1970s, increase again, and then gradually decrease from 1982 to 1990 (see Figure 7). Second, the peak season of use for livestock grazing on the YTC was April through July, with additional use in the late fall and early winter (see Figure 8). Finally, average AUMs per acre decreased consistently across all grazing units from 1965 to 1995, whereas total number of acres grazed increased from 1965 to 1981, but decreased from 1981 to 1995 (see Figures 9 and 10). AUM data were not available for each year of the 5-year grazing lease between 1960 and 1970. For this time period,

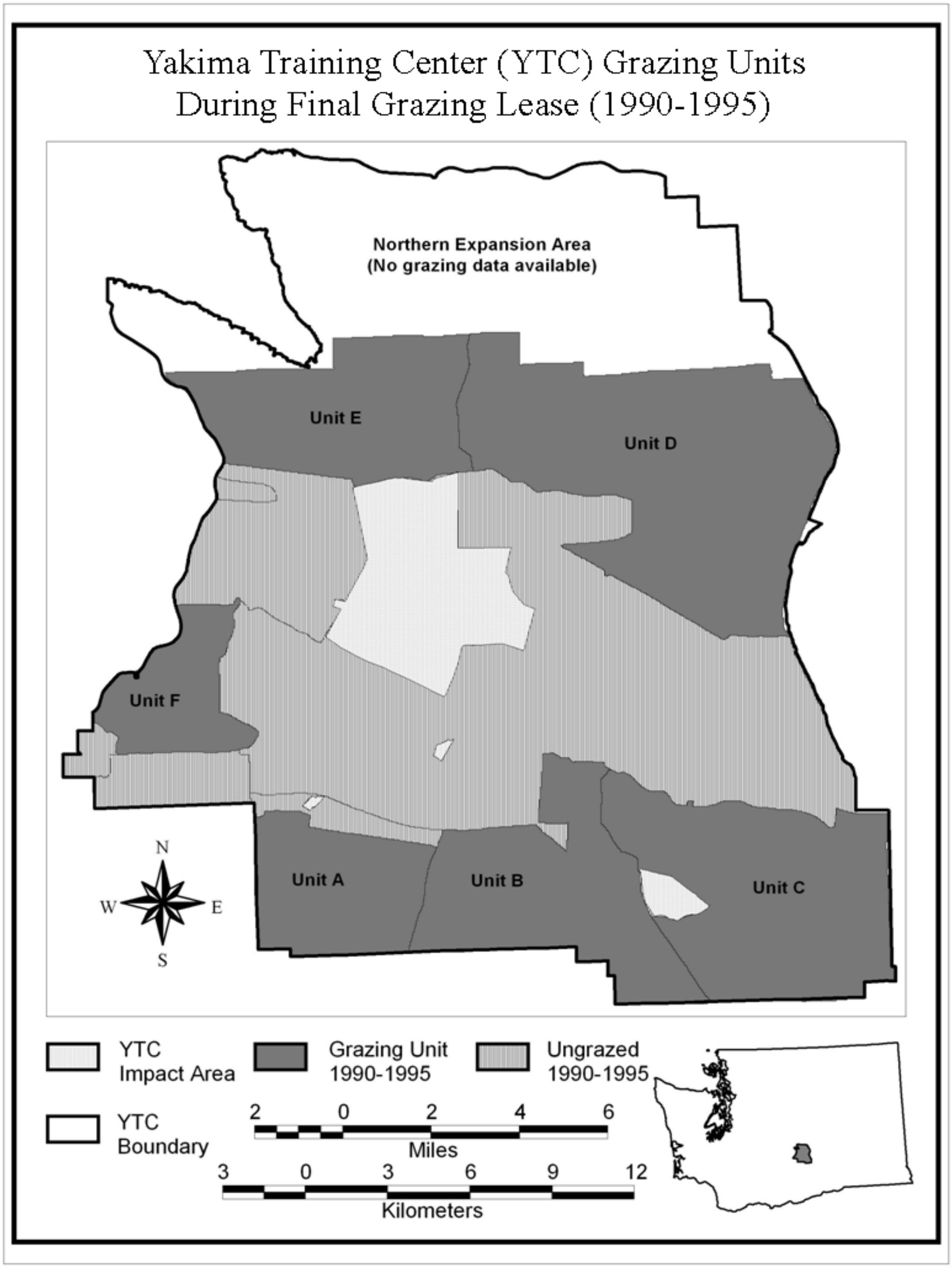

Figure 6. Yakima Training Center livestock grazing lease units and ungrazed areas during the final lease period (1990-1995).

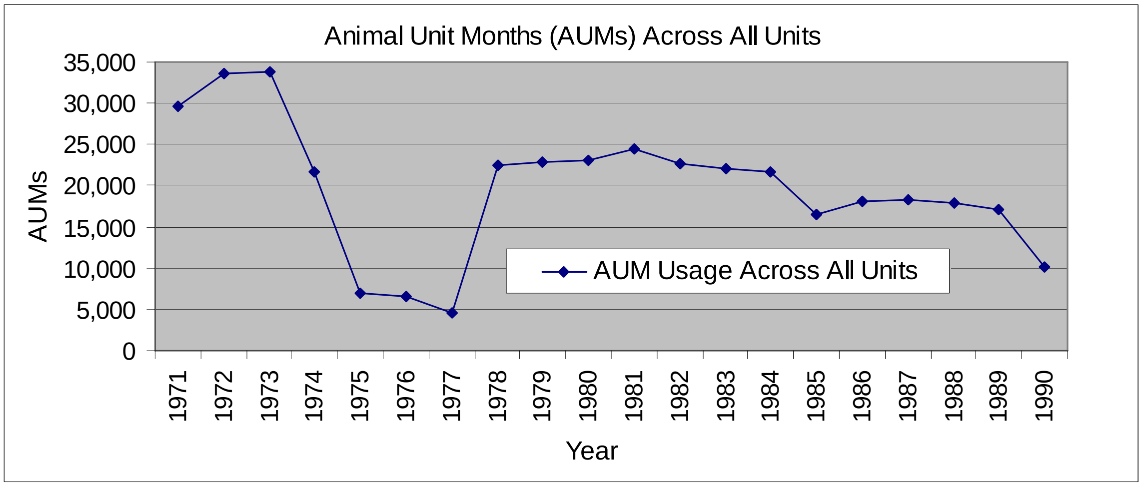

Figure 7. Animal unit months allocated across all Yakima Training Center grazing units between 1971 and 1990.

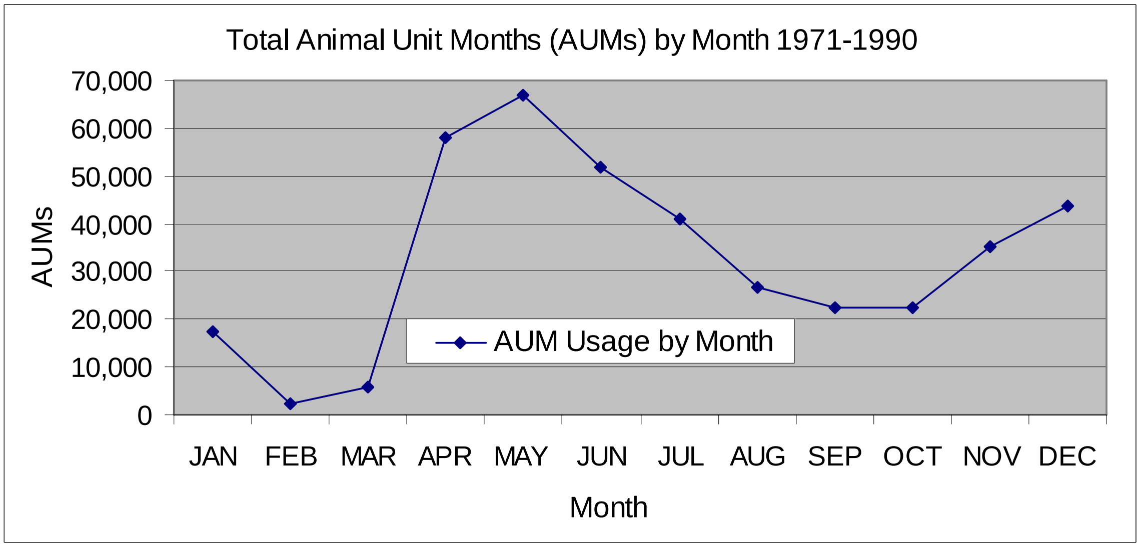

Figure 8. Total animal unit months allocated at the Yakima Training Center by month between 1971 and 1990.

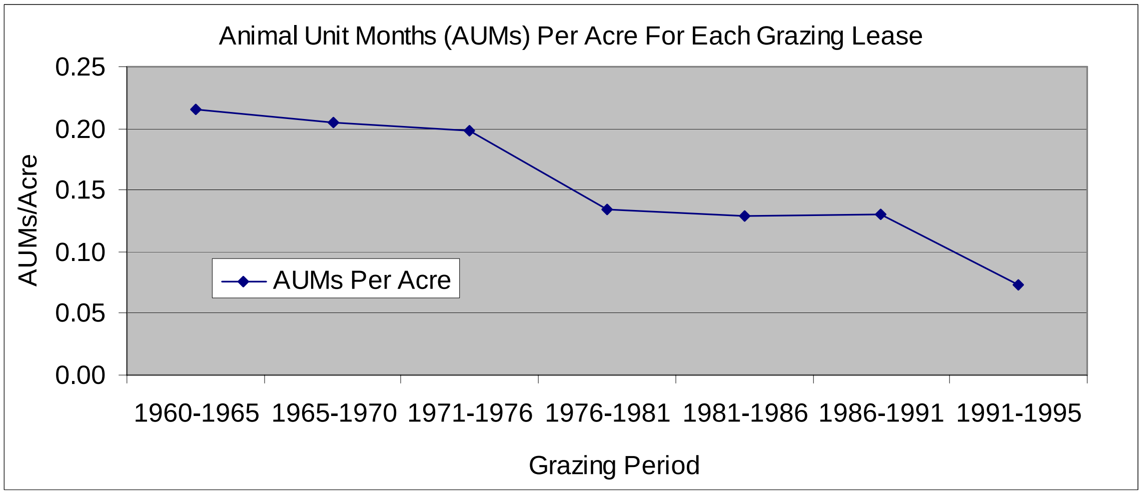

Figure 9. Average animal unit months allocated per acre at the Yakima Training Center during each grazing lease period from 1960 to 1995.

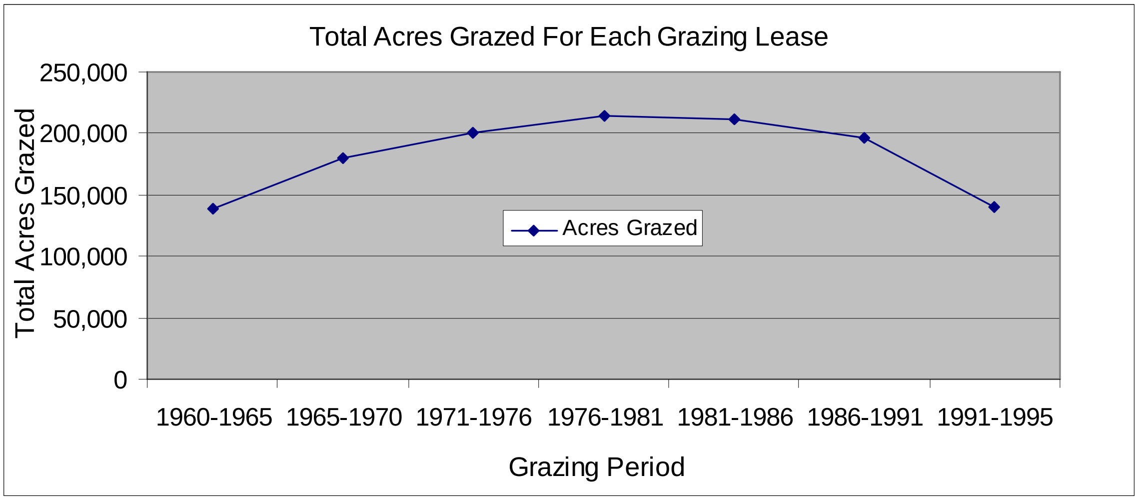

Figure 10. Total acres grazed at the Yakima Training Center during each grazing lease period from 1960 to 1995.

average AUMs per acre and total acres grazed were available for the entire grazing lease and not broken down by year. These trends suggest that grazing intensity generally decreased across the entire length of recorded livestock grazing history at the YTC, and management practices evolved to a more environmentally conscious state. In general, trends of fewer acres grazed over time and fewer AUMs per month indicate that the YTC's range management program evolved from allowing more abundant and widespread livestock utilization to managing for a more constricted area of allowable use and less time for forage utilization.

Accurate descriptions of livestock grazing on historic YTC and the Northern Expansion Area are not available because locations of heavily utilized versus lightly utilized grazing pastures were not recorded. Livestock grazing was officially removed from the YTC in its entirety as of 1995. For these reasons, some assumptions about the overall impact of livestock grazing will be included.

Biological soil crust cover and composition may increase as degree or percentage of slope increases because livestock show greater use on gentle slopes than on steep slopes. Studies designed to track and observe livestock utilization have suggested that 80% or more of all livestock grazing within a given pasture or allotment will occur on slopes of less than 20% (Heady & Child, 1994). In fact, 75% utilization was noted for the first 32 ft of a 60% slope, while the same amount of utilization was noted for 740 ft of a 10% slope (Mueggler, 1965; see Figure 11). Also, Julander and Jeffery (1964) noted that cattle mostly utilize slopes of less than 10%.

Military Training

Training activity was minimal on the YTC until the period of 1956 to 1965, followed by a period of low activity between 1965 and 1972 (U.S. Department of the Army, 1978). Another period of heavy activity followed, peaking in 1976 with the

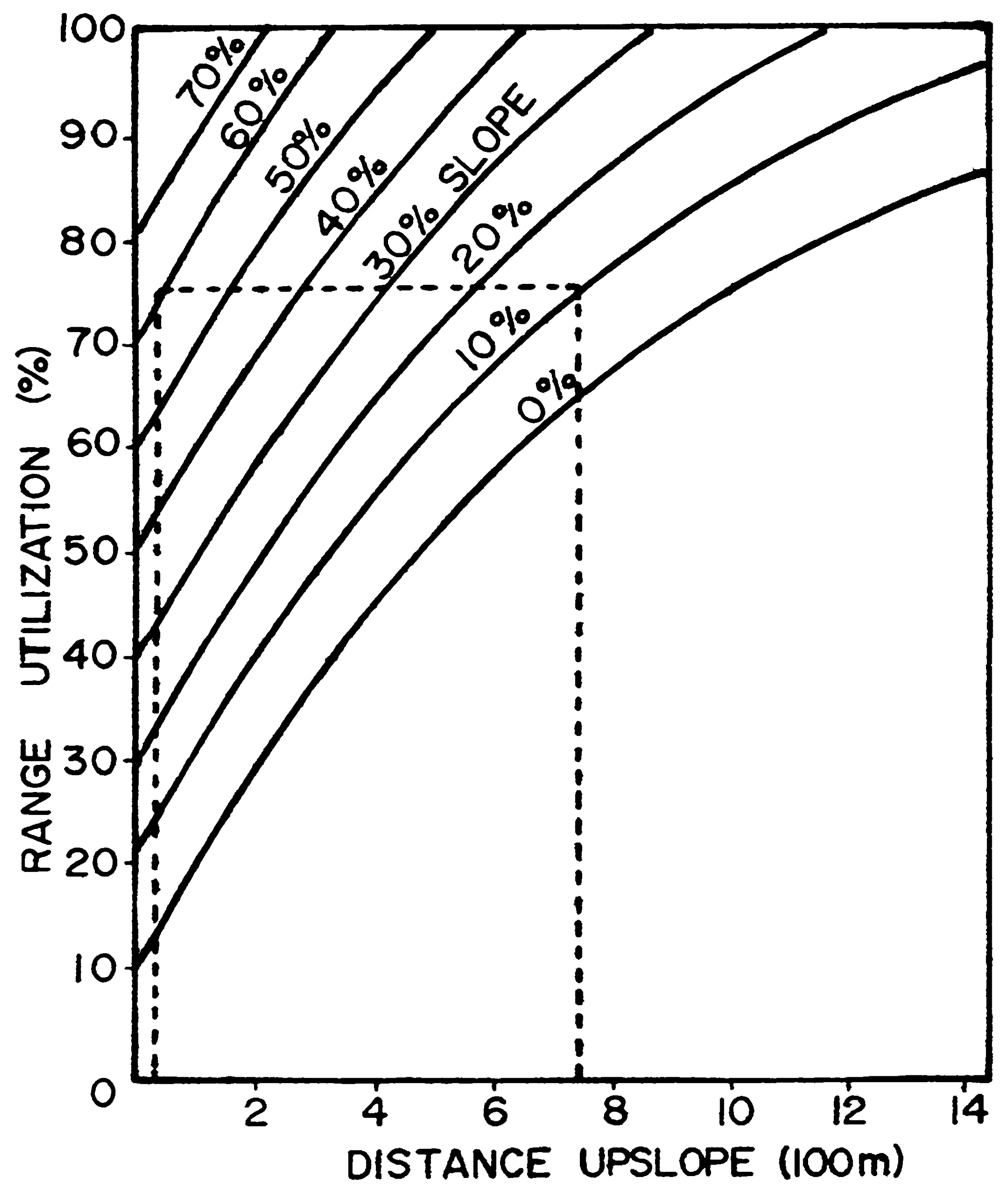

Figure 11. Influence of slope steepness and distance upslope on use of range by cattle. From Mueggler (1965).

largest training activity conducted to date called JTX Brave Shield XIV, which included 26,000 soldiers (U.S. Department of the Army).

After 1978, another period of lower activity followed, until the period 1989 to 1991, when training activity increased during preparation for Operation Desert Storm (Bern, 1996a). LCTA data collection during the same period showed that military training impacted 70%-75% of the original 202 LCTA plots over the course of 3 years. LCTA data collection in 1994 showed the number of plots impacted by military training was reduced to only 40% from 1991 (Bern, 1996a).

Training activities continued at lower levels until Cascade Sage 1995 and the Washington Army National Guard 1996 exercises took place. Together, these two exercises impacted 128 acres with high-use activities and 9,445 acres with moderate-use activities. Moderate activity is described as numerous vehicle tracks, small areas of newly exposed soil, and some degraded vegetation cover, while heavy activity is described as removal of 95%-100% of existing land cover (Stephan et al., 1996). Also, 2,039 acres of land were moderately used during both exercises and 4 acres of land were heavily used during both exercises. No other large-scale training events occurred during the period 1989 to 2002.

From the time when LCTA was first implemented in 1989, training usage on the YTC appears to have been dispersed across the entire installation, with the exception of the Northern Expansion Area, which was not acquired until 1994. As of 2002, YTC training areas having received high usage, or moderately high usage during this period are Training Areas 16, 12, and 11, along with Assembly Areas 1, 2, and 3 (see Figure 12

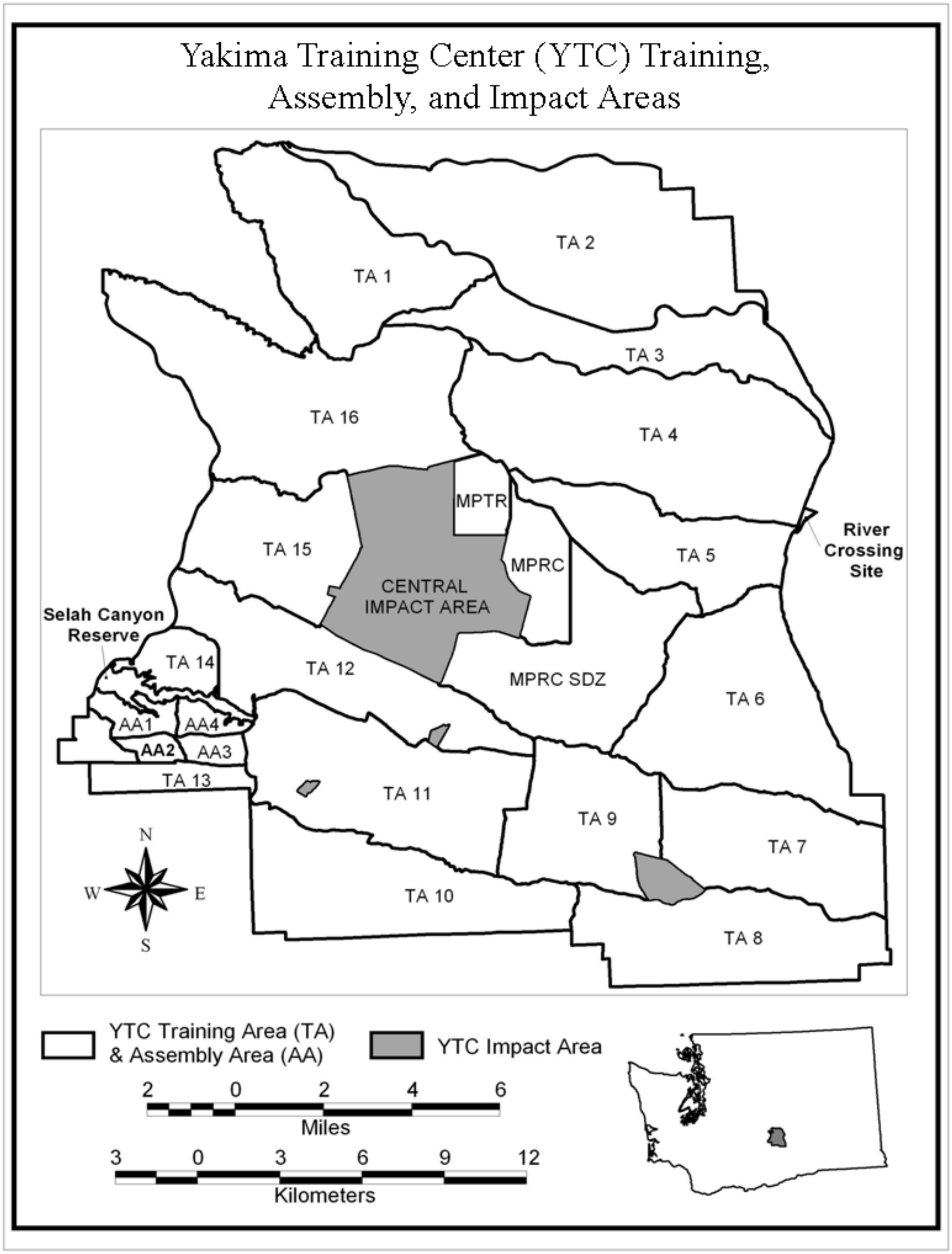

Figure 12. Yakima Training Center training area boundaries.

and Table 3). Those areas having received moderate training usage are Training Areas 1, 4, 7, and 10, while those areas having received low or low-moderate training usage are Training Areas 2, 3, 5, 6, 8, 9, 14, and 15.

Because training use appears to have been relatively well dispersed, it will be assumed that training activities have occurred somewhat equally across the terrain where access and slope have permitted. Thus, areas with steep slopes and poor access have received lower military training impacts. For example, the 1996 LCTA report noted that in general military training occurred on average on 4.7% to 9.7% slopes (Bern, 1996a). Also, Cadwell, Reid, Simmons, and Nugent (1996) noted that new track cover decreased with slope because only 1.1% of new track cover was observed for all land area having slopes greater than 9°. And finally, the YTC's Sage Grouse Management Plan notes that lands conducive to military training exist in areas with slopes less than or equal to 10% (ENRD, 1998).

Military training, because of its use of motorized vehicles, has a greater impact on biological soil crust than other forms of mechanical disturbance, such as recreational hunting and hiking, traditional cultural uses, or livestock grazing. Vehicles tend to churn the soil and bury soil crust components, whereas trampling compacts the surface and may only break apart soil crust components (Belnap & Eldridge, 2001). A study completed in the western steppe region of Idaho suggested that tank maneuvers on military training lands had a significant impact on the total cover of biological soil crust (Watts, 1998).

Table 3

Off-Road Military Usage by Training Area at the Yakima Training Center for 2002

Training area	Training usage	Training usage notes
TA 16	High	Extensive maneuver usage, concentrated support areas.
TA 12	High	Selah maneuver corridor, extensive maneuver and concentrated-use areas.
AA1	High	Close to cantonment and small arms ranges. Concentrated use areas in level terrain, less maneuver on slopes.
AA2	High	Close to cantonment and small arms ranges. Concentrated use areas in level terrain, less maneuver on slopes.
AA3	High	Close to cantonment and small arms ranges. Concentrated use areas in level terrain, less maneuver on slopes.
TA 11	Moderate-high	Live fire ranges and maneuver areas. Extensive road/trail/firebreak system, some off-road maneuvers, fires common.
TA 1	Moderate	Some localized high-use areas, overall access somewhat limited.
TA 4	Moderate	Extensive use for maneuver on and off trails. Some localized high-use areas.
TA 7	Moderate	Used as corridor to TA 6, western portion provides broad and gentle maneuver terrain. Remote location limits usage.
TA 10	Moderate	Some localized high-use areas and occasional use for larger exercises, overall access is somewhat limited.
TA 2	Low-moderate	Rugged terrain and remote area with limited access.
TA 3	Low	Remote training area with limited access, some extensive and localized use.
TA 5	Low	Remote training area, some extensive and localized use.
TA 6	Low	Remote training area, some extensive and localized use.
TA 8	Low	Remote training area, some extensive and localized use.
TA 9	Low	Some extensive and localized use. Grouse protection area with seasonal and other restrictions.
TA 14	Low	Grouse protection area with seasonal and other restrictions. Limited off-road travel.
TA 15	Low	Grouse protection area with seasonal and other restrictions. Limited off-road travel.

Note. TA = training area; AA = assembly area. Adapted from Jones and Kunze (2003).

Fire

Since 1987, fire has impacted approximately 27% of the YTC's approximately 327,242 acre land area, or more than 88,000 acres (ENRD, 2004). A large portion of this impact occurred in the Corral Creek and Alkali Creek subwatersheds located in the eastern portion of the installation, which experienced large-scale catastrophic fires in 1996 and 2003. A majority of these watersheds also burned in 1984 (ENRD). This pattern of repeated large-scale catastrophic fires and the abundance of fire experienced over the past 17 years is most likely related to increased fuels from the removal of livestock grazing, conversion of sagebrush steppe to grassland steppe caused by land use activities, and increased cover of cheatgrass (*Bromus tectorum*) brought on by a combination of livestock grazing and military training activities. Cheatgrass is known to have increased fire frequency on shrub-steppe rangelands elsewhere in western North America (Johansen, 2001).

A great deal of fire disturbance also occurs in association with the YTC's firing ranges and the Central Impact Area. In relation to LCTA's 262 core plots (see Figure 13), 71 plots have burned at least once in the past 16 years, while 191 have not burned according to fire data from 1987 to 2003. Of those 71 plots, 32 have burned twice in the last 16 years, 3 have burned three times, and only 1 plot has burned four times. Not a single plot has burned more than five times between 1987 and 2003.

Biological soil crusts are thought to be negatively affected by fire disturbance in a number of ways, depending upon location and fire intensity, frequency, and magnitude. Reductions in cover, changes in composition, and alteration of ecosystem function such

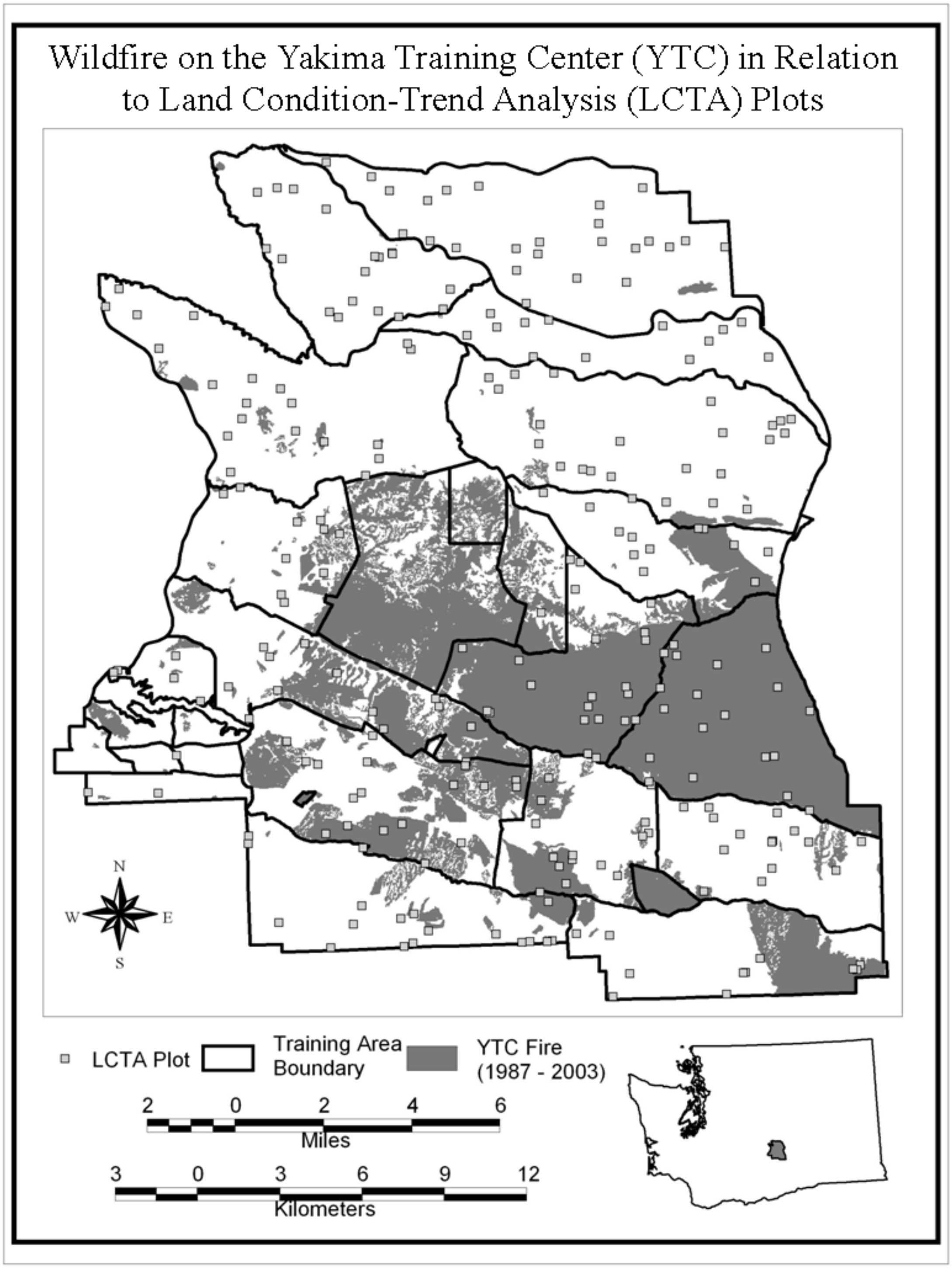

Figure 13. Total fire disturbance at the Yakima Training Center occurring between 1987 and 2003 in relation to the Land Condition-Trend Analysis plots.

as reduced nitrogen fixation, higher susceptibility to wind and water erosion, and lower rates of water infiltration are considered to be the most notable changes (Johansen, 2001). Several studies show significant declines in biological soil crust cover, including greatly decreased moss and lichen cover observed at Washington State's Hanford National Monument's Arid Lands Ecology Reserve as a result of fire (Johansen).

Recovery from fire can vary greatly depending upon intensity and severity of the fire, climate, and location. Johansen (2001) discusses recovery rates of 5 years for photosynthetic biomass in Great Basin locations and more rapid recovery in Washington. Johansen also discusses recovery rates of 4-7 years for mosses and 13-35 years for lichens in semiarid rangelands of Australia, and no recovery after 37 years in some blackbrush communities. Cryptogam cover was shown to peak between 13 and 16 years, and to be significantly less (< 20%) 7 years after fire in an Australian shrubland (Eldridge & Bradstock, 1994). These results show the great variability in recovery rates across locations and differences in climate regimes.

Other Human Uses

Other human uses of the YTC fall into two main categories that include traditional cultural use and outdoor recreation. Traditional cultural use refers to hunting and gathering rights within the boundaries of the YTC guaranteed to Native Americans as part of the Treaty of 1855 (Beckham, 1995; Boreson, 1998; Owens, 2005). Outdoor recreation primarily refers to the YTC hunting program, which includes upland game bird, elk, and deer hunting (ENRD, 2001). Impacts of these uses on biological soil crusts are probably minimal for two reasons, the numbers of people participating in each use is limited and usage normally occurs during short periods of time.

Relationships Between Variables

Many components of upland ecosystems have direct and indirect influences on composition of biological soil crusts. Topographic position, or slope, aspect, and elevation, is an important variable to consider because of relationships with disturbance patterns and biological soil crust structure. Relationships exist between intensity of disturbance and landscape slope. Off-road vehicle use and livestock grazing have similar detrimental impacts on biological soil crusts, which include trampling and destruction of crust components (Warren & Eldridge, 2001). Therefore, it is assumed that historic grazing on the YTC will be similar to military use in that heavier use has been observed on slopes less than 10% (Bern, 1996a). Biological soil crust cover and composition may exhibit characteristics of later successional stages on sites with slopes in excess of 15%-20%.

Aspect is important for assessing the composition and condition of biological soil crusts. North-facing slopes generally support greater soil crust cover due to increased availability of moisture (Belnap & Lange, 2001). This is usually true unless vascular plant cover increases to the point of restricting soil crust development.

The relationship between soil texture and biological soil crust composition is such that fine-textured soils will support communities with greater cover and diversity as compared with coarse-textured soils (Belnap & Lange, 2001). Soil chemistry relates to biological soil crusts in that soils with carbonates tend to support an increased abundance of phycolichens and lichen diversity, while soils with increased salinity restrict soil crust cover (Belnap & Lange).

Certain relationships exist between vascular plant species and biological soil crusts. Ponzetti and McCune (2000) found that cheatgrass (*Bromus tectorum*) had a negative relationship between total crust cover and species richness, while native species such as bluebunch wheatgrass (*Pseudoroegneria spicata*) and Sandberg's bluegrass (*Poa secunda*) experienced a positive relationship. This suggests that stands of relatively less disturbed native vegetation should support greater soil crust abundance and diversity as compared to stands of introduced annual grass.

Biological soil crusts have evolved with anthropogenic disturbances, including fire manipulation by indigenous peoples. This manipulation historically produced a patchwork mosaic, often leaving islands of unburned vegetation and soil crust that may have aided in recolonization (Rosentreter et al., 2001). Due to increased disturbance from domesticated animal grazing and human use, vascular plant communities have often experienced shifts to higher densities of woody shrubs or grasslands comprised of exotic annuals (Brooks & Pyke, 2001; Grant Count Public Utility District, 2002). These factors have resulted in changes to wildfire frequency and intensity. It is assumed that biological soil crust communities have been negatively impacted by the amount of livestock, fire, and military training disturbances at the YTC.

Strong relationships exist between morphological characteristics of crust organisms and disturbance. For example, relative abundance of some short moss species such as *Bryum* and *Ceratodon* may increase following fire disturbance, while tall mosses and lichens decrease (Kaltenecker, 1997). Other studies have shown a relationship between disturbed sites and “weedy” moss and lichen species, as well as a correlation between sites of stable condition and later successional “leafy” species of lichen (Eldridge & Koen, 1998; Eldridge & Rosentreter, 1999).

CHAPTER 4

METHODS

Biological soil crust morphological groups, dimensionality groups, lichens, mosses, and total crust cover were sampled along permanently established transects at LCTA plots. Also, environmental variables were measured to determine relationships with biological soil crust condition and composition. Measurements included (a) collection of soil surface samples of no more than 2.5 cm depth for determining soil texture, pH, and level of nitrogen, phosphorus, and potassium; (b) proportion of vascular plants; (c) proportion of litter, rock, and bare ground; (d) proportion of biological soil crust morphological groups and dimensionality groups; and (e) presence or absence of vehicle disturbance along each transect. In addition, slope and elevation at each transect were determined through the use of geographic information systems (GIS).

Selection of Transects

YTC's LCTA recently utilized 262 core plots for routine monitoring of landscape condition, which were established randomly and stratified to represent the major vegetation and soil types across the YTC landscape (Bern, 1996a). For this thesis, 81 plots were selected using a random numbers table. Plots were selected only from the original 262 core LCTA plots, until sufficient transects were selected to represent each of the three habitat types, shrub-steppe, dwarf shrub-steppe, and grass-steppe, as defined in chapter 3, encompassing the YTC (see Figure 14). Sample sizes for each habitat type were calculated using LCTA data collected during 2003.

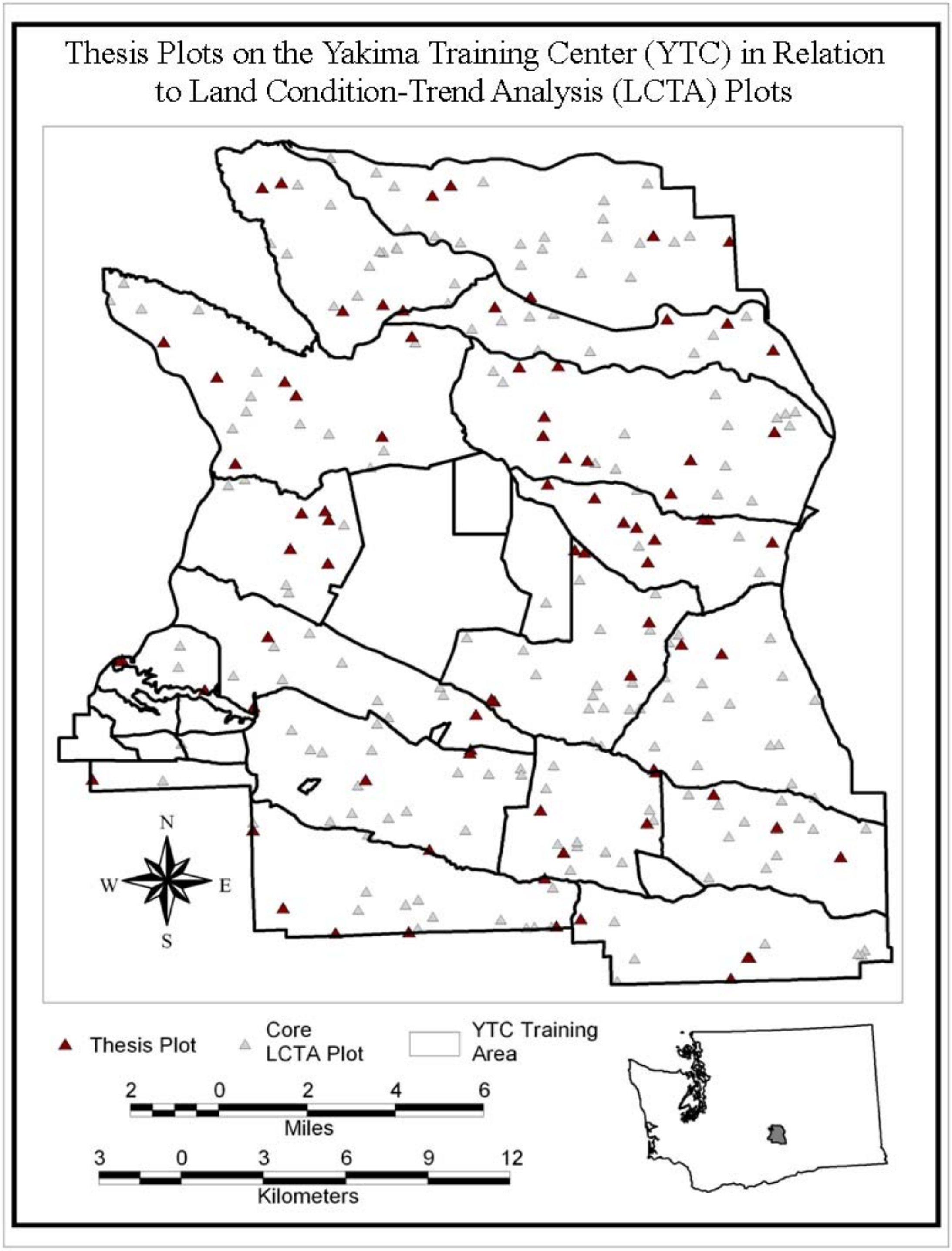

Figure 14. Selected thesis plots in comparison to remaining Yakima Training Center Land Condition-Trend Analysis plots.

During 2003, LCTA efforts sampled transects within the Moxee and Cold Creek subwatersheds (see Figure 15). Use of biological soil crust morphological groups was also implemented at this time. Ground cover data from 8 transects of dwarf shrub-steppe, 15 transects of grass-steppe, and 9 of shrub-steppe habitat types were used to calculate sample sizes using the following equation:

$$n = \frac{(Z)^2(SD)^2}{(B)^2}$$

This equation determines the proper sample size for estimating a population mean with a specified level of precision, where Z is the standard normal coefficient obtained from a specified confidence interval, SD is the standard deviation, and B is the desired precision level (Elzinga, Salzer, & Willoughby, 1998). For determining the proper sample size of LCTA transects to be sampled, Z is 1.64 (determined using a 90% confidence interval), SD was the standard deviation calculated from ground cover data within each habitat type, and B was calculated using a 20% confidence interval width and the sample mean for total crust cover across all of the 32 transects sampled in 2003 (i.e., 20% × sample mean, or 20% × 21.4 = 4.28). Sample size equations yielded suggested sample sizes of 7 dwarf shrub-steppe, 27 grass-steppe, and 12 shrub-steppe. To ensure comparisons between habitat types were equal, sample sizes of dwarf shrub-steppe and shrub-steppe plots were increased to 27.

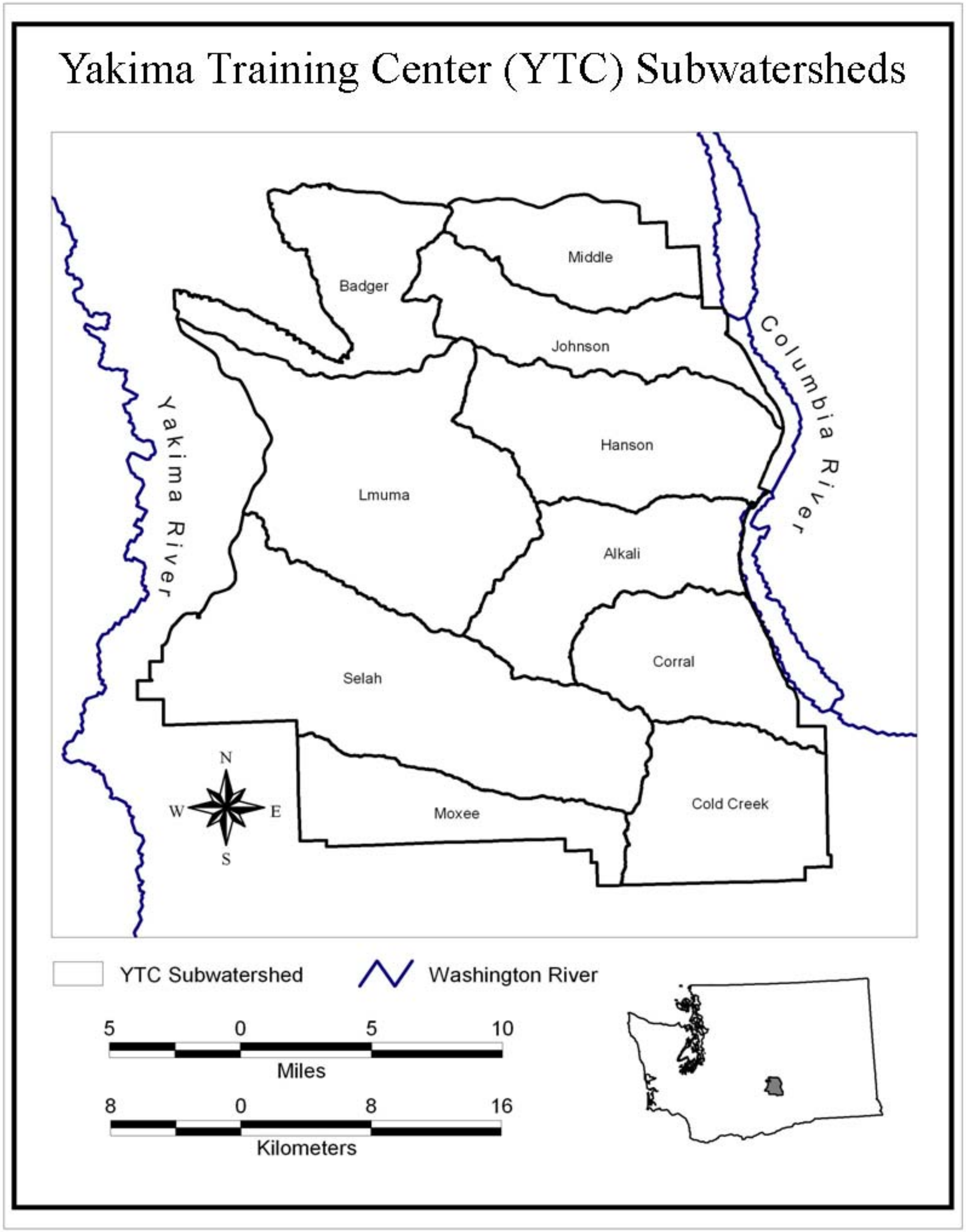

Figure 15. Yakima Training Center subwatersheds within Yakima River and Columbia River watersheds.

Data Collection Along Transects

Along each transect data were collected in the following manner. First, permanent LCTA plots were located in the field using GPS coordinates, a metal detector, and site photographs. LCTA transects have pins at 0 m, 25 m, 50 m, 75 m, and 100 m, and only the 0-m pin, or head pin has a GPS position associated with it. Upon locating each plot with a GPS and metal detector, a portion of a 100-m measuring tape was strung between the 25-m pin and the 50-m pin. Data collection began at the 30-m mark because it was assumed that disturbance to the landscape surrounding starting points of LCTA transects would be much greater than near the middle of each transect.

Starting from the 30-m mark and facing toward the 100-m ending point, the left-hand side was used for point-line intercept and line intercept data collection. Biological soil crust morphological group cover; dimensionality group cover; total crust cover; ground cover, including rock, bare ground, and litter; vascular plant cover; and vehicle disturbance variables were recorded using point-line intercept and line intercept techniques until reaching 50 m. Morphological groups included tall moss, short moss, crustose lichen, squamulose lichen, foliose lichen, and fruticose lichen. Gelatinous lichen was not included as a morphological group because of difficulty differentiating gelatinous lichens in the field noted during the 2003 pilot study. Therefore, gelatinous lichens, if encountered, were lumped into the morphological groups they most closely resembled (i.e., crustose or foliose).

At every 0.5-m mark, the point-line intercept method was used to gather data, resulting in 40 ground hits or points per transect. A metal rod, with pointed tip, was placed against the measuring tape at each 0.5-m interval and used to record the first "ground hit" (i.e., morphological group, litter, rock, bare ground, or vascular plant cover) encountered on the ground surface. If a morphological group was recorded, then it was placed into the proper dimensional group (i.e., one dimensional, two dimensional, or three dimensional). Also, aerial cover of dominant vascular plant was recorded, if present, at each interval. Past vehicle disturbance data, noted as either single pass or trail, were recorded for each point intercept as well. The point-line intercept sampling technique was generally rapid, taking no more than 15 to 20 min per transect.

Following completion of the point-line intercept method, the line intercept method was used to gather data at each transect. Line intercept involved characterizing every centimeter intersecting the tape into morphological group, dimensionality group, total crust cover, ground cover, and/or vascular plant cover. All variables were recorded to the nearest centimeter, and if a variable covered smaller than a centimeter along the line, it was not counted. Similar to point-line intercept, morphological groups were placed into dimensionality groups if recorded. Also, vehicle disturbance and vascular plant aerial cover were noted, where present, along each centimeter of the line intercept. The line intercept sampling technique was generally time consuming, taking 2 or more hours per transect.

During both point-line intercept and line intercept, clearly distinguishable lichen and moss species were recorded as the number of each specific morphological group encountered at that transect (i.e., Crustose 1, Crustose 2, Crustose 3, etc.). Upon completion of sampling, voucher specimens for the various numbered morphological groups were collected for future identification and for development of a lichen and moss reference collection that can be used to aid in training and identification during future monitoring efforts.

The dimensionality index was calculated using the proportion of each dimensionality group at a given transect. The dimensionality index was calculated by taking the distance along each line, or number of points along each line, of a given dimensionality group, expressed as a percentage, multiplied by the dimension (i.e., one, two, or three), then divided by the largest dimension (i.e., three) and summed for the entire transect (Rosentreter & Eldridge, 2004). The idea here is that a transect composed of 30% cover of tall moss, a three-dimensional species, would have a higher dimensionality index when compared to a transect composed of 30% cover of crustose lichen, a two-dimensional species.

Slope data and fire history were acquired from YTC's GIS data for each plot. Fire data have been mapped using satellite imagery at the YTC following each wildfire season dating back to 1989. Slope data were acquired from GIS using YTC's digital elevation model, calculated by YTC staff using ArcGIS software (Environmental Systems Research Institute, Inc., 2006).

Soil Data Analysis

Soil surface samples were collected at 30 m, 40 m, and 50 m along each transect at no more than 2.5 cm depth for laboratory analysis of soil texture, pH, and nitrogen, phosphorus, and potassium levels. Soil texture analysis was conducted for each sample using the hydrometer method (Gee & Bauder, 1979). An IQ Scientific Instruments, Inc.

(Carlsbad, CA) electronic pH-meter was also used to determine pH level for each soil sample. A soil slurry with 10 mL water and 10 g soil was mixed for use with the pH-meter (K. Lillquist, personal communication, August 15, 2004). Instructions for the IQ Scientific Instruments pH-meter were carefully followed and buffer solutions surrounding expected values were used.

Soil texture and pH results were each averaged ($N = 3$) for each transect and used to describe the mean condition of soils at each transect. Lamotte Company (Chester, MD) nitrogen-phosphorus-potassium test kits were used to test levels of each nutrient in soil samples. Test kits returned results of low, medium, or high for each nutrient. Averaging for macronutrient tests was not possible because test results were broad rankings and not quantitative values.

Biological Soil Crust Data Analysis

Statistical analysis of line intercept and point-line intercept data was conducted with a suite of multivariate community analysis techniques available from PC-Ord® software (McCune & Mefford, 1999). This statistical package was chosen because PC-Ord® works well for analysis of nonnormal datasets typical of ecological communities.

Nonparametric multidimensional tests, designed specifically for community relationship analysis of ecological datasets, were used. Specifically, blocked multiresponse permutation procedure (MRBP), indicator species analysis (ISA), and nonparametric multidimensional scaling (NMS) were all utilized for testing differences between line intercept and point-line intercept techniques.

Prior to using any of the analyses mentioned above, the data were analyzed for normality, to see if data needed to be transformed, and outliers, to see if certain plots needed to be removed from analyses. Looking at the individual variables, to include morphological groups, ground cover, and vascular plant variables, a majority were highly skewed because of a high number of 0 values. Outlier analysis in PC-Ord, using Euclidean distance measures, showed only a very small number of plots as outliers for each sampling technique. It was decided that outliers would not be removed from the analyses because the outlier analysis showed that these plots were not extreme outliers and information that might be provided from these outliers was desirable in the analyses.

Blocked Multiresponse Permutation Procedure

MRBP tests the null hypothesis of no significant difference between two or more groups within each block, or pair (McCune & Grace, 2002). For this experiment, MRBP was used in testing the hypothesis of no difference between point-line intercept and line intercept sampling techniques with blocks or pairs being the 81 plots. In addition, MRBP was used to test the hypothesis of no difference between point-line intercept and line intercept sampling techniques in each habitat type with blocks or pairs being the 27 plots in each habitat type. MRBP provides a simple test statistic, or *p* value for the difference among groups. For more accurately describing differences among groups, McCune and Grace suggest overlaying variables that define groups on an ordination of sample units and describing the indicator value of indicator species among groups. ISA was chosen to more accurately describe differences among groups, while NMS was chosen to explore relationships between biological soil crust and environmental variables.

The Euclidean distance measure, recommended by McCune and Mefford (1999) for use with ecological community data, was used to run MRBP to test the null hypothesis of no difference between groups. Morphological group data and ground cover data including rock, bare ground, and litter for all plots were grouped together in the primary matrix, with sampling technique as the grouping variable and the 81 plots as the blocking variable in the secondary matrix. Data were transformed using the arcsine-squareroot transformation. This transformation is recommended by McCune and Grace (2002) for proportion data as it often improves the normality of data. MRBP was run to test the difference between sampling techniques, pairing mean values of the two sampling techniques at each plot. In addition, plots were grouped into the three habitat types, 27 plots each for shrub-steppe, grass-steppe, and dwarf shrub-steppe, and MRBP was run to test the difference between sampling techniques within each habitat type, again pairing mean values of the two different sampling techniques at each plot.

Indicator Species Analysis

ISA is a method for detecting and describing the value of different species for indicating environmental conditions. For the purpose of this experiment, ISA was used to observe any differences in sampling techniques for describing the value of morphological groups for indicating habitat type and any difference between disturbed versus undisturbed plots. Disturbed plots were grouped as those plots having experienced fire over the past 17 years or military training disturbance recorded during data collection efforts. ISA combines information about the abundance of a particular species in a group with its faithfulness of occurrence within that group (McCune &

Grace, 2002). Ideally, a perfect indicator would be extremely abundant within a group and would only occur within that group.

ISA was used to contrast performance of morphological groups across habitat types and disturbed versus undisturbed plots for both sampling techniques. In other words, for this experiment, ISA was used to describe which morphological groups were strong indicators of habitat type or disturbed versus undisturbed plots depending on the specific sampling technique used. Data were transformed using the arcsine squareroot transformation as suggested by McCune and Grace (2002) for proportion data. Morphological group data from all plots for each sampling technique were grouped into two separate primary matrices for running the analysis. Two secondary matrices were used for each sampling technique, one with habitat type as the grouping variable and the other with disturbance, including fire or vehicle disturbance, or lack of disturbance as the grouping variable. ISA tests were subject to 1,000 randomizations used in the Monte Carlo test, which is the suggested number utilized for ecological community datasets (McCune & Meffert, 1999).

Nonmetric Multidimensional Scaling

NMS is an ordination technique, or procedure for arranging plots along multiple axes, that is often used for nonnormal ecological community data and is generally considered the most effective method for this type of data (McCune & Grace, 2002). For this experiment, NMS was used as a gradient analysis technique for arranging the plots in multidimensional space and overlaying biological soil crust and environmental variables to include slope, elevation, soil texture and pH, vascular plant composition, total crust cover, and dimensionality index across those sample units. The overlays allow for the ability to observe relationships between individual variables and the sample units.

NMS is an iterative search for the best fit of samples in a multidimensional space (McCune & Grace, 2002). For the purpose of this experiment, PC-Ord was utilized by running the software initially on autopilot. The autopilot procedure performs multiple runs with the real data and multiple runs with randomized data, selects the best solutions defined by a particular starting configuration and number of dimensions, and selects the proper dimensionality by comparing final stress values among the best solutions (McCune & Mefford, 1999). Mean morphological group and ground cover variables were grouped for all plots from both sampling techniques into one primary matrix. Data were transformed using the arcsine squareroot transformation. Environmental variables including slope, elevation, soil texture and pH, vascular plant composition, total crust cover, and dimensionality index for all plots were grouped together in a secondary matrix with morphological groups and ground cover variables. Data in this matrix were transformed differently than mentioned above. Using a general relativization by column, pH and elevation were relativized to the slope and soil texture data. Relativizations rescale individual columns in relationship to other columns. In this case, slope and soil texture were percentages, while elevation data were in meters and pH data were values from 6 to 9. In order to place these variables with different measurement units on equal footing a relativization was needed. Sorensen distance measure was used as the recommended distance measure for ecological data (McCune & Mefford).

Methods for Determining Appropriate Recommendations

Upland ecosystem monitoring at the YTC is currently experiencing a paradigm shift, in which traditional plot-based LCTA monitoring of upland ecosystems is transitioning to qualitative monitoring with focus on military training impacts. As an employee of the YTC and a member of the RTLA committee, I am responsible for providing technical input into the future of upland ecosystem monitoring at the YTC. Given the importance of biological soil crusts in arid and semiarid environments, as described in chapter 2, the recommendations from this thesis will be part of the technical input provided to YTC natural resource managers during the process of RTLA protocol development.

CHAPTER 5

RESULTS AND DISCUSSION

Baseline Biological Soil Crust Data

Biological soil crust morphological group and dimensionality group data were collected along 81 permanently placed transects at 81 LCTA plots across the YTC, including 27 plots each for dwarf shrub-steppe, shrub-steppe and grass-steppe habitat types. Data were collected using two techniques, line intercept and point-line intercept. In addition to biological soil crust data, ground cover, vascular plant cover, soil texture, soil chemistry, vehicle disturbance, fire history, percentage slope, and elevation data were collected or compiled for each plot. Representative collections of each biological soil crust species encountered were also collected at each plot. This data collection effort provides the YTC with baseline biological soil crust data stratified by YTC's three major habitat types, shrub-steppe, dwarf shrub-steppe, and grass-steppe.

Analysis of Biological Soil Crust Sampling Techniques

Prior to statistical analysis, mean percentage and standard deviation of ground-cover values for morphological groups, total crust cover, dimensionality index, ground cover components, and vascular plant species were calculated from each sampling technique for all plots and habitat types (see Tables 4, 5, 6, 7 and 8).

Nearly all variables were nonnormal and it was decided that standard descriptive statistics would not be utilized to test for differences between sampling techniques. Mean values were very similar between sampling techniques for all plots and habitat types. Notable differences between sampling techniques were that mean proportions of

Table 4

Percentage of Morphological Groups and Ground Cover

	Line intercept		Point line-intercept	
Variable	Mean	*SD*	Mean	*SD*
All plots (*N* = 81)				
Crustose lichen	0.0294	0.0414	0.0278	0.0385
Foliose lichen	0.0012	0.0032	0.0012	0.0067
Fruticose lichen	0.0007	0.0043	0.0006	0.0039
Squamulose lichen	0.0366	0.0519	0.0358	0.0550
Short moss	0.0254	0.0389	0.0250	0.0367
Tall moss	0.1070	0.1117	0.0889	0.0952
Total crust cover	0.2003	0.1465	0.1793	0.1316
Dimensionality index	0.1818	0.1336	0.1606	0.1193
Bare ground	0.2131	0.1640	0.2259	0.1580
Litter	0.3182	0.1965	0.3426	0.1889
Rock	0.1838	0.2133	0.1670	0.1942
Shrub-steppe plots (*n* = 27)				
Crustose lichen	0.0360	0.0496	0.0324	0.0379
Foliose lichen	0.0011	0.0034	0.0009	0.0048
Fruticose lichen	0.0021	0.0074	0.0019	0.0067
Squamulose lichen	0.0436	0.0475	0.0380	0.0446
Short moss	0.0428	0.0546	0.0361	0.0477
Tall moss	0.1061	0.1173	0.0907	0.1070
Total crust cover	0.2317	0.1581	0.2000	0.1390
Dimensionality index	0.2045	0.1418	0.1765	0.1259
Bare ground	0.1920	0.1630	0.2037	0.1434
Litter	0.4079	0.1555	0.4306	0.1556
Rock	0.0779	0.1352	0.0750	0.1282
Grass-steppe plots (*n* = 27)				
Crustose lichen	0.0294	0.0424	0.0278	0.0424
Foliose lichen	0.0007	0.0025	--	--
Fruticose lichen	0.0495	0.0612	0.0519	0.0743
Squamulose lichen	0.0231	0.0303	0.0231	0.0339
Short moss	0.0740	0.0976	0.0611	0.0859

Table 4 (continued)

	Line intercept		Point line-intercept	
Variable	Mean	*SD*	Mean	*SD*
Tall moss	0.1768	0.1510	0.1639	0.1396
Total crust cover	0.1596	0.1370	0.1460	0.1267
Dimensionality index	0.2230	0.1543	0.2324	0.1538
Bare ground	0.3999	0.2080	0.4213	0.1882
Litter	0.0975	0.1181	0.0806	0.0864
Rock	0.0294	0.0424	0.0278	0.0424
Dwarf shrub-steppe plots (*n* = 27)				
Crustose lichen	0.0229	0.0304	0.0231	0.0360
Foliose lichen	0.0018	0.0038	0.0028	0.0106
Short moss	0.0167	0.0405	0.0176	0.0345
Squamulose lichen	0.0102	0.0143	0.0157	0.0221
Tall moss	0.1409	0.1130	0.1148	0.0870
Total crust cover	0.1926	0.1288	0.1741	0.1174
Dimensionality index	0.1813	0.1223	0.1593	0.1069
Bare ground	0.2243	0.1780	0.2417	0.1784
Litter	0.3761	0.2236	0.3454	0.2062
Rock	0.1469	0.0750	0.1759	0.0831

Note. Dashes indicate variable not recorded at transects in this group.

Table 5

Percentage of Vascular Plants at All Plots

	Line intercept		Point line-intercept	
Variable	Mean	*SD*	Mean	*SD*
Crested wheatgrass	0.0085	0.0451	0.0086	0.0486
Stiff sagebrush	0.0340	0.0588	0.0278	0.0511
Big sagebrush	0.0589	0.0964	0.0534	0.0901
Three-tip sagebrush	0.0043	0.0260	--	--
Astragalus	0.0017	0.0066	0.0022	0.0106
Hooker's balsamroot	0.0028	0.0117	0.0022	0.0098
Cheatgrass	0.0662	0.1370	0.0593	0.1302
Rubber rabbitbrush	0.0004	0.0021	--	--
Green rabbitbrush	0.0016	0.0106	0.0025	0.0129
Hawksbeard	0.0009	0.0045	0.0015	0.0072
Squirreltail	0.0019	0.0071	0.0031	0.0107
Willowherb	0.0007	0.0034	0.0009	0.0048
Linearleaf daisy	0.0015	0.0045	0.0019	0.0086
Rock buckwheat	0.0058	0.0214	0.0062	0.0232
Thymeleaf buckwheat	0.0065	0.0163	0.0059	0.0154
Six weeks fescue	0.0003	0.0023	--	--
Idaho fescue	0.0156	0.0553	0.0164	0.0594
Lomatium	0.0013	0.0050	0.0025	0.0094
Lupine	0.0067	0.0196	0.0080	0.0285
Indian ricegrass	0.0028	0.0199	--	--
Hood's phlox	0.0033	0.0123	0.0037	0.0138
Longleaf phlox	0.0042	0.0116	0.0025	0.0094
Cusick's bluegrass	0.0067	0.0247	0.0086	0.0375
Sandberg's bluegrass	0.1227	0.0789	0.1522	0.1055
Bluebunch wheatgrass	0.1605	0.1895	0.1651	0.1902
Russian thistle	0.0082	0.0356	0.0080	0.0351
Goldenweed	0.0137	0.0259	0.0130	0.0268
Thurber's needlegrass	0.0090	0.0200	0.0083	0.0190
Large headed clover	0.0010	0.0040	--	--

Note. Dashes indicate variable not recorded at transects in this group.

Table 6

Percentage of Vascular Plants at Shrub-Steppe Plots

	Line intercept		Point line-intercept	
Variable	Mean	*SD*	Mean	*SD*
Stiff sagebrush	0.0075	0.0238	0.0074	0.0248
Big sagebrush	0.1486	0.1095	0.1361	0.1036
Three-tip sagebrush	0.0107	0.0433	--	--
Astragalus	0.0023	0.0080	0.0028	0.0144
Cheatgrass	0.0469	0.0786	0.0407	0.0613
Rubber rabbitbrush	0.0009	0.0034	--	--
Green rabbitbrush	0.0034	0.0178	0.0037	0.0192
Hawksbeard	0.0004	0.0021	0.0019	0.0067
Squirreltail	0.0004	0.0021	0.0009	0.0048
Willowherb	0.0004	0.0020	0.0009	0.0048
Linearleaf daisy	0.0009	0.0028	0.0019	0.0096
Rock buckwheat	0.0068	0.0248	0.0056	0.0244
Idaho fescue	0.0000	0.0000	--	--
Lomatium	0.0320	0.0822	0.0352	0.0897
Lupine	0.0003	0.0016	0.0009	0.0048
Indian ricegrass	0.0160	0.0307	0.0204	0.0460
Hood’s phlox	0.0017	0.0063	--	--
Longleaf phlox	0.0030	0.0154	0.0028	0.0144
Cusick’s bluegrass	0.0056	0.0113	0.0037	0.0091
Sandberg’s bluegrass	0.0145	0.0370	0.0176	0.0518
Bluebunch wheatgrass	0.0859	0.0746	0.1065	0.0939
Russian thistle	0.2382	0.1957	0.2370	0.1849
Goldenweed	0.0008	0.0041	0.0009	0.0048
Thurber’s needlegrass	0.0099	0.0251	0.0120	0.0313
Large headed clover	0.0170	0.0276	0.0167	0.0259

Note. Dashes indicate variable not recorded at transects in this group.

Table 7

Percentage of Vascular Plants at Grass-Steppe Plots

	Line intercept		Point line-intercept	
Variable	Mean	*SD*	Mean	*SD*
Crested wheatgrass	0.0255	0.0763	0.0259	0.0825
Stiff sagebrush	0.0045	0.0165	0.0056	0.0200
Big sagebrush	0.0280	0.0603	0.0241	0.0574
Three-tip sagebrush	0.0023	0.0119	--	--
Astragalus	0.0028	0.0082	0.0037	0.0114
Hooker's balsamroot	0.0032	0.0092	0.0037	0.0150
Cheatgrass	0.1259	0.2006	0.1130	0.1988
Rubber rabbitbrush	0.0002	0.0010	--	--
Green rabbitbrush	0.0015	0.0051	0.0037	0.0114
Hawksbeard	0.0023	0.0074	0.0028	0.0106
Squirreltail	0.0017	0.0090	0.0019	0.0096
Willowherb	0.0018	0.0054	0.0019	0.0067
Linearleaf daisy	0.0013	0.0041	0.0019	0.0067
Rock buckwheat	0.0011	0.0057	0.0009	0.0048
Thymeleaf buckwheat	0.0016	0.0058	0.0000	0.0000
Six weeks fescue	0.0009	0.0040	--	--
Idaho fescue	0.0135	0.0458	0.0130	0.0467
Lomatium	0.0002	0.0013	0.0000	0.0000
Lupine	0.0042	0.0101	0.0037	0.0114
Indian ricegrass	0.0066	0.0341	--	--
Hood's phlox	0.0003	0.0014	0.0009	0.0048
Longleaf phlox	0.0042	0.0113	0.0019	0.0096
Cusick's bluegrass	0.0056	0.0199	0.0083	0.0386
Sandberg's bluegrass	0.1319	0.0852	0.1630	0.1086
Bluebunch wheatgrass	0.2237	0.1992	0.2370	0.2075
Russian thistle	0.0238	0.0591	0.0231	0.0584
Goldenweed	0.0067	0.0178	0.0056	0.0174
Thurber's needlegrass	0.0071	0.0172	0.0037	0.0133
Large headed clover	0.0014	0.0048	--	--

Note. Dashes indicate variable not recorded at transects in this group.

Table 8

Percentage of Vascular Plants at Dwarf Shrub-Steppe Plots

	Line intercept		Point line-intercept	
Variable	Mean	*SD*	Mean	*SD*
Stiff sagebrush	0.0899	0.0702	0.0704	0.0647
Hooker's balsamroot	0.0053	0.0179	0.0028	0.0080
Cheatgrass	0.0257	0.0741	0.0241	0.0652
Squirreltail	0.0036	0.0080	0.0065	0.0149
Linearleaf daisy	0.0023	0.0061	0.0019	0.0096
Rock buckwheat	0.0096	0.0268	0.0120	0.0313
Thymeleaf buckwheat	0.0179	0.0240	0.0176	0.0228
Six weeks fescue	0.0001	0.0005	--	--
Idaho fescue	0.0015	0.0064	0.0009	0.0048
Lomatium	0.0034	0.0081	0.0065	0.0149
Hood's phlox	0.0068	0.0142	0.0074	0.0181
Longleaf phlox	0.0029	0.0123	0.0019	0.0096
Sandberg's bluegrass	0.1503	0.0638	0.1870	0.1003
Bluebunch wheatgrass	0.0194	0.0373	0.0213	0.0431
Goldenweed	0.0244	0.0306	0.0213	0.0283
Thurber's needlegrass	0.0028	0.0081	0.0046	0.0121
Large headed clover	0.0012	0.0047	--	--

Note. Dashes indicate variable not recorded at transects in this group.

morphological groups, for the most part, were higher for the line intercept sampling technique as compared to the point-line intercept sampling technique (Table 4).

Looking only at standard deviation, one sampling technique did not appear to be more variable than the other, at least not as consistently as with morphological groups captured by the line intercept technique. In addition, the line intercept sampling technique captured a greater diversity of vascular plant species than the point-line intercept sampling technique in all three habitat types and across all plots. For all plots combined, the line intercept sampling technique captured 29 different species, while the point-line intercept sampling technique captured 24 (Table 5). For plots in the dwarf shrub-steppe habitat type, the line intercept sampling technique captured 17 different species, while the point-line intercept sampling technique captured 15 (Table 6). For plots in the shrub-steppe habitat type, the line intercept sampling technique captured 25 species, while the point-line intercept sampling technique captured 21 (Table 8). And for the grass-steppe habitat type, the line intercept sampling technique captured 29 species and the point-line intercept sampling technique captured 24 species (Table 7).

Results discussed above showed some important differences between sampling techniques and suggest that the line intercept sampling technique provided a richer dataset, but do not indicate which of the two biological soil crust sampling techniques are more appropriate for crust monitoring purposes. Therefore, the next step in analyzing results of this experiment was to use MRBP to test the null hypothesis of no significant difference between groups with a blocked design. MRBP tested the hypothesis of no difference between biological soil crust morphological groups and ground cover data collected by the line intercept and point-line intercept sampling techniques, with each plot paired, or blocked for the analysis. In addition, the same analysis was run with plots separated for each habitat type. Results from MRBP for all habitat types show that chance-corrected within group agreement (A) and p value ($p = .05$) were significant and the null hypothesis had to be rejected. Thus, there was a significant difference between the results of the sampling techniques both when combining all plots and within each habitat type (see Table 9).

Table 9

Blocked Multiresponse Permutation Procedure Results

Habitat type	A	*p*
All plots	0.03964365	0.00000004*
Shrub-steppe	0.03902569	0.00673707*
Grass-steppe	0.02493676	0.02386836*
Dwarf shrub-steppe	0.04436221	0.00140226*

Note. A = within group chance-corrected agreement. All plots $N = 81$, shrub-steppe plots $n = 27$, grass-steppe plots $n = 27$, dwarf shrub-steppe plots $n = 27$.
$^*p < .05$.

MRBP only provides a test statistic, or a *p* value, to say that, compositionally, the plots were different based upon the sampling technique used to obtain data. ISA was used to further explore the differences between biological soil crust sampling techniques. In other words, ISA is a test that will help describe the difference between the two sampling technique datasets. This can be done by analyzing the capability of those datasets for yielding indicators of habitat type and disturbed versus undisturbed plots.

ISA tested the potential of data collected by each sampling technique to yield biological soil crust morphological groups as indicators of habitat type and disturbed versus undisturbed plots. With all plots separated by sampling technique and grouped by habitat type or disturbed versus undisturbed plots, ISA selected the strongest relationship to a specific group (i.e., habitat type or disturbed versus undisturbed plots) for each morphological group.

Results of ISA show that data collected by the line intercept technique yielded three morphological groups as indicators of the various habitat types (*p* values were considered significant at .10 or less; see Table 10). A significant indicator of shrub-steppe habitat was the morphological group squamulose lichen, while both tall moss and foliose lichen were significant indicators of the dwarf shrub-steppe habitat type. Results of ISA show that data collected by the point-line intercept technique yielded only one morphological group as a significant indicator; tall moss was a significant indicator of the dwarf shrub-steppe habitat.

Table 10

Indicator Species Analysis Results for Plots Grouped by Habitat Type

Morphological group	Habitat type	Line intercept *p*	Point-line intercept *p*
Crustose lichen	Shrub-steppe	0.76	0.84
Foliose lichen	Dwarf shrub	0.01*	0.55
Fruticose lichen	Shrub-steppe	0.12	0.31
Short moss	Grass-steppe	0.22	0.31
Squamulose lichen	Shrub-steppe	0.01*	0.24
Tall moss	Dwarf shrub	0.08*	0.06*

Note. Line intercept yielded 3 indicators of various habitat types, while point-line intercept yielded only 1 indicator. Morphological groups that yielded insignificant indicators of various habitat types were still reported because they were the most abundant in that particular habitat type.
$p^* \leq .10$.

Results of ISA show that data collected by the line intercept technique yielded one morphological group as an indicator of undisturbed plots (see Table 11). The morphological group squamulose lichen was an indicator of undisturbed plots. Results of

Table 11

Indicator Species Analysis Results for Plots Grouped by Disturbance

Morphological group	Group	Line intercept *p*	Point-line intercept *p*
Crustose lichen	Undisturbed	0.22	0.42
Foliose lichen	Undisturbed	0.44	0.49
Fruticose lichen	Undisturbed	0.39	0.55
Short moss	Undisturbed	0.89	0.96
Squamulose lichen	Undisturbed	0.10*	0.62
Tall moss	Undisturbed	0.14	0.25

Note. Line intercept yielded one indicator of undisturbed plots, while point-line intercept failed to yield any indicators. Only "Undisturbed" was present in the "Group" column because morphological groups were not more abundant in "Disturbed" plots.
$p^* \leq .10$.

ISA for the point-line intercept technique did not yield any significant indicators of disturbed or undisturbed plots.

In comparing the biological soil crust sampling techniques and their ability to yield indicators of habitat type and disturbed versus undisturbed plots, the line intercept sampling technique outperformed the point-line intercept sampling technique by yielding more significant indicators in both sets of analysis. These results, coupled with MRBP results, provide further evidence suggesting that the adequacies of each technique for sampling soil crust yielded significantly different compositions. Analysis results from MRBP showed that sampling techniques were significantly different, while analysis results from ISA show how the sampling techniques are different.

NMS ordinations were performed utilizing a primary matrix of the percentage of composition of morphological groups, bare ground, rock, and litter for each plot and for each sampling technique, or 9 variables by 162 plots (81 plots for each sampling technique). The final NMS ordination had three axes with a final stress of 12.09 and a final instability of .0049. The three-axes solution explained a total of 88.2% of the variation in the data. Varimax rotation, explained as the most common rotation technique used for ordinations (McCune & Grace, 2002), was used to improve the interpretability of the ordination because it tends to find groups of sample units that correspond more closely. Following varimax rotation, Axis 1 explained 43.9% of the variation in the data, while Axes 2 and 3 explained 20% and 24.2%, respectively. Figure 16 displays a graphical representation of Axis 1 and Axis 3. The combination of Axes 1 and 3 explained a combined 68.1% of the variation in the dataset. The combination of Axes 1 and 2 explained 63.9%, but was not explored in detail.

Axis 1 can be summarized showing several interrelated gradients, the first reflects a gradient ranging from coarse soil texture to fine soil texture. Percentage of silt (r = 0.447) is negatively correlated with the axis, while percentage of sand (r = 0.394) and percentage of gravel (r = 0.527) are positively correlated with the axis (Figure 16; Tables 12 and 13). Axis 1 also reflects a gradient ranging from shrub-steppe habitats to dwarf-shrub steppe habitats, with species found in shrub steppe habitats being negatively correlated with the axis, such as bluebunch wheatgrass (r = −0.548) and big sagebrush (r = −0.377), and species found in dwarf shrub-steppe habitats being positively correlated with the axis, such as stiff sagebrush (r = 0.359) and thymeleaf buckwheat (r = 0.403; Tables 12 and 13). In addition, a gradient in biological soil crust morphological groups and ground cover variables is reflected in this axis, with short moss (r = −0.472),

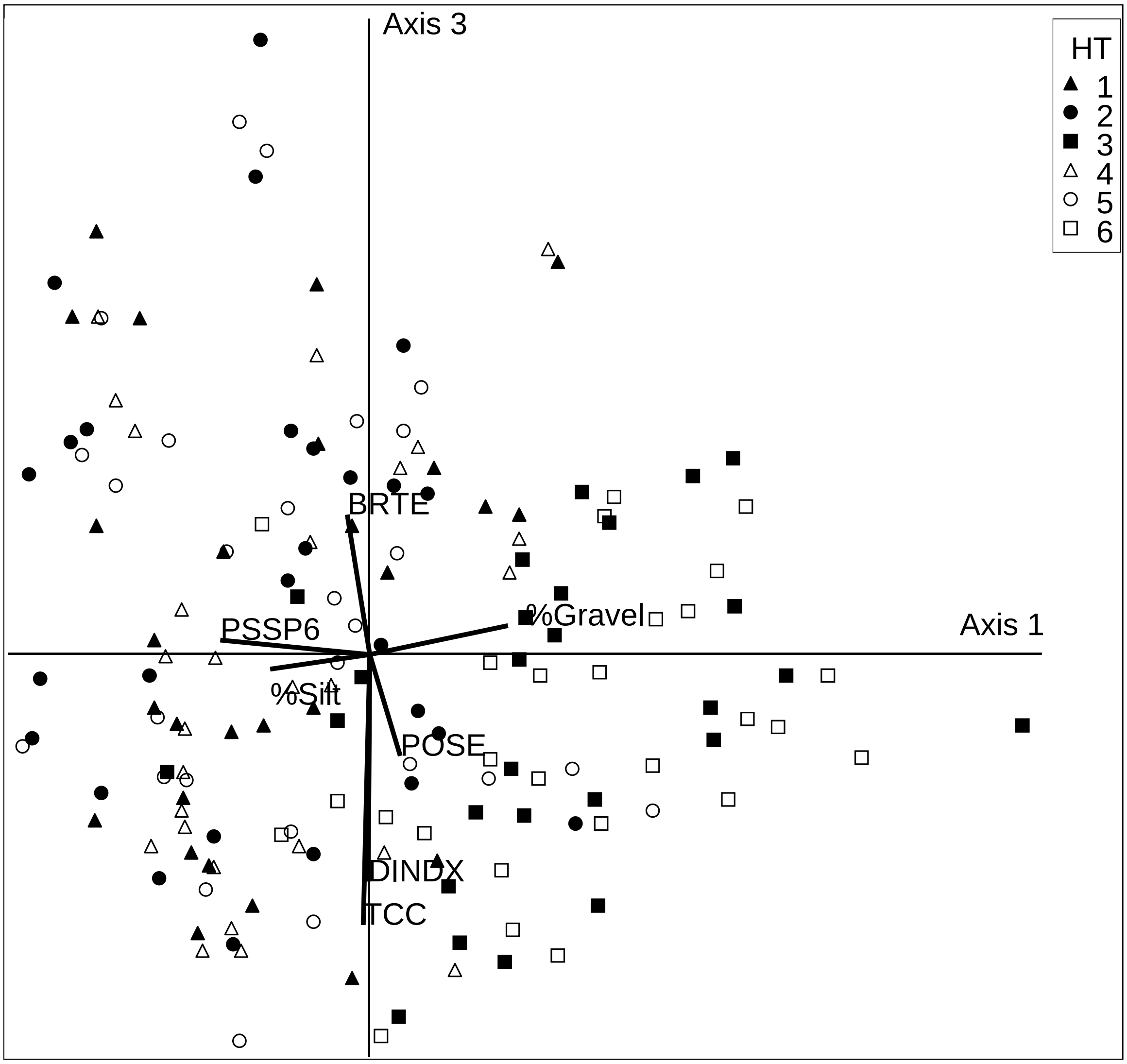

Figure 16. Nonmetric multidimensional scaling ordination of all plots read with the line intercept and point-line intercept techniques grouped by habitat type and sampling technique. HT = habitat type; 1 = shrub-steppe line intercept; 2 = grass-steppe line intercept; 3 = dwarf shrub-steppe line intercept; 4 = shrub-steppe point-line intercept; 5 = grass-steppe point-line intercept; 6 = dwarf shrub-steppe point-line intercept; BRTE = cheatgrass; PSSP6 = bluebunch wheatgrass; %Gravel = percentage of gravel; %Silt = percentage of silt; POSE = Sandberg’s bluegrass; DINDX = dimensionality index; TCC = total crust cover.

Table 12

Correlation Values (Pearson's r) for all Ground Cover Variables at All Plots

Variable	Axis 1	Axis 2	Axis 3
Crustose lichen	−0.173	0.349	−0.426
Foliose lichen	0.102	0.112	−0.234
Fruticose lichen	−0.010	0.391	0.031
Short moss	−0.472	0.505	−0.095
Squamulose lichen	−0.359	0.479	−0.409
Tall moss	0.301	0.277	−0.748
Bare ground	−0.178	−0.822	−0.311
Litter	−0.674	0.308	0.687
Rock	0.944	−0.231	0.111

Note. Correlation values for morphological groups and ground cover variables were calculated from the primary matrix.

Table 13

Correlation Values (Pearson's r) for All Vascular Plants, Soil Texture, pH, Slope, and Elevation at All Plots

Variable	Axis 1	Axis 2	Axis 3
Percentage of sand	0.394	−0.455	0.211
Percentage of clay	0.087	0.018	−0.232
Percentage of silt	−0.447	0.487	−0.172
Percentage of gravel	0.527	−0.288	0.240
Slope	0.060	0.101	0.203
Elevation	0.117	0.001	−0.054
pH	0.104	−0.161	−0.004
Crested wheatgrass	−0.113	0.140	0.157
Stiff sagebrush	0.359	−0.093	−0.210
Big sagebrush	−0.377	0.209	−0.056
Three-tip sagebrush	−0.042	0.198	0.085
Astragalus	−0.080	0.215	0.021

Table 13 (continued)

Variable	Axis 1	Axis 2	Axis 3
Hooker’s balsamroot	0.215	−0.007	−0.026
Cheatgrass	−0.213	0.033	0.528
Rubber rabbitbrush	−0.078	−0.110	−0.078
Green rabbitbrush	−0.188	0.150	0.020
Hawksbeard	−0.173	0.090	−0.045
Squirreltail	0.121	−0.159	−0.114
Willowherb	0.088	−0.056	0.087
Linearleaf daisy	−0.005	−0.303	−0.066
Rock buckwheat	0.259	−0.066	0.052
Thymeleaf buckwheat	0.403	−0.138	−0.063
Six weeks fescue	−0.078	0.008	−0.021
Idaho fescue	−0.130	0.351	0.132
Lomatium	0.181	−0.111	−0.153
Lupine	−0.188	0.195	0.157
Indian ricegrass	−0.029	0.055	−0.008
Hood’s phlox	0.134	−0.036	−0.219
Longleaf phlox	−0.029	0.236	−0.237
Cusick’s bluegrass	−0.091	0.261	−0.235
Sandberg’s bluegrass	0.249	0.118	−0.449
Bluebunch wheatgrass	−0.548	0.313	0.173
Russian thistle	−0.211	0.026	0.409
Goldenweed	0.222	−0.103	−0.317
Thurber’s needlegrass	−0.172	0.049	−0.092
Large-headed clover	0.102	−0.051	−0.098
Total crust cover	−0.115	0.584	−0.735
Dimensionality index	−0.054	0.504	−0.674

Note. Correlation values for vascular plants, soil texture, pH, slope, and elevation were calculated from the secondary matrix. Vascular plant names followed by “point” represent correlations of point-line intercept data. Vascular plant names followed by “line” represent correlations of line intercept data. Vascular plant names by themselves represent correlations of vascular plants in general.

squamulose lichen ($r = -0.359$), and litter ($r = -0.674$) all negatively correlated with the axis, while tall moss ($r = 0.301$) and rock ($r = 0.944$) were positively correlated with the axis (Figure 16; Tables 12 and 13).

Axis 3 can be summarized as showing a gradient ranging from biological soil crust, native vascular plant species, and bare ground to introduced vascular plant species and litter. Crustose lichen ($r = -0.426$), squamulose lichen ($r = -0.409$), tall moss ($r = -0.748$), bare ground ($r = -0.311$), total crust cover ($r = -0.735$), dimensionality index ($r = -0.674$), Sandberg's bluegrass ($r = -0.449$), and goldenweed ($r = -0.317$) were all negatively correlated with Axis 3 (Figure 16; Tables 12 and 13). Cheatgrass ($r = 0.528$), Russian thistle ($r = 0.409$), and litter ($r = 0.687$) were all positively correlated with Axis 3 (Figure 16; Tables 12 and 13).

Ordination results were relatively similar between sampling techniques for plots grouped by habitat type. When comparing the location of plots in three-dimensional space in relation to the gradients explained previously, it appears as though plots from the three different habitat types were aligning for the most part in groups, and that a relatively equal number from each sampling technique were present in each of these groups. For example, 23 dwarf shrub-steppe plots from the line intercept sampling technique and 24 dwarf shrub-steppe plots from the point-line intercept sampling technique were present on the right half of the ordination, versus 4 and 3 located on the left half of the ordination (Figure 16), indicating more dwarf shrub-steppe plots were present where variables such as stiff sagebrush, thymeleaf buckwheat, percentage of sand, percentage of gravel, tall moss, and rock were increasing (Tables 12 and 13). In addition, 15 grass-steppe plots from the line intercept sampling technique and 14 from the point-line intercept sampling technique are present on the top half of the ordination, versus 12 and 13 located on the bottom half of the ordination (Figure 16), indicating slightly more grass-steppe plots were present where variables such as cheatgrass, Russian thistle, and litter were increasing (Tables 12 and 13). Shrub-steppe plots were relatively equally represented on the left half of the ordination with 21 plots from the line intercept sampling technique and 20 from the point-line intercept sampling technique, versus 6 and 7 located on the right half of the ordination (Figure 16), indicating that more shrub-steppe plots were present where variables such as big sagebrush, bluebunch wheatgrass, percentage of silt, short moss, squamulose lichen, and litter were present (Tables 12 and 13). And finally, relatively equal representation from both dwarf shrub-steppe plots and shrub-steppe plots were present in the bottom half of the ordination, with 17 line intercept and 20 point-line intercept dwarf shrub-steppe plots, versus 10 and 7 located on the top half, and 13 line intercept and 16 point-line intercept shrub-steppe plots, versus 14 and 11 located on the top half (Figure 16), indicating that more plots in dwarf shrub-steppe and shrub-steppe were present where variables such as crustose lichen, squamulose lichen, tall moss, total crust cover, dimensionality index, goldenweed, Sandberg's bluegrass, and bare ground were present (Tables 12 and 13).

These relationships, for the most part, compare well with biological soil crust relationships discussed in recent literature. For example, recent literature in biological soil crust relationships with soil texture suggests that greater cover and diversity of biological soil crusts occur on fine textured soils (Belnap, Prasse, et al., 2001).

According to relationships explained along Axis 1, diversity of morphological groups was greater on fine textured soils than on coarse textured soils, with short moss and squamulose lichen correlated with fine textured soil and only tall moss correlated with coarse textured soil. However, greater crust cover may not have been more abundant on coarse textured soils. Tall moss was recorded as being the most abundant morphological group, but was correlated with coarse textured soil. In addition, both techniques also reflected a gradient ranging from increasing cover of cheatgrass and litter ground cover to increasing cover of biological soil crust. Ponzetti and McCune (2000) also found that biological soil crust cover was inversely related to cheatgrass cover. Additional recent literature speaks to the contrary relationship of increased litter and organic matter to biological soil crust cover (Belnap, Prasse, et al.).

Other relationships explained by ordinations of both techniques include the following. A majority of shrub-steppe plots were generally aligned with biological soil crust variables, while grass-steppe plots were generally aligned with cheatgrass and Russian thistle (Figure 16; Tables 12 and 13). This relationship associates well with the nature of grass-steppe habitats on YTC mostly resulting from the conversion of shrub-steppe habitats by past wildfire (ENRD, 2004). Additionally, the gradient observed along Axis 1 of the ordination (Figure 16) showed tall moss increasing with variables common to dwarf shrub-steppe habitats such as stiff sagebrush, thymeleaf buckwheat, rock, and coarse-textured soil, whereas short moss and squamulose lichen increased with variables common to shrub-steppe habitats such as big sagebrush and bluebunch wheatgrass (Tables 12 and 13). This relationship of tall moss being positively correlated with dwarf shrub-steppe habitat types is not supported by any known recent literature. However, the relationship is supported by results from ISA, which show that both line intercept and point-line intercept sampling techniques yielded tall moss as a significant indicator of dwarf shrub-steppe habitat types (Tables 10 and 11).

Another relationship is explained when plots were grouped by past wildfire (see Figure 17). A greater number of plots experiencing wildfire in the past 17 years were present on the top half of the ordination, aligning more closely with greater cheatgrass and Russian thistle cover, whereas a greater number of plots not experiencing wildfire align more closely with biological soil crust variables in the bottom half of the ordination (Figure 17; Tables 12 and 13). This relationship closely parallels the relationship between grass-steppe and shrub-steppe habitat types discussed above because conversion from shrub-steppe to grass-steppe has primarily occurred as a result of wildfire. Nearly 27% of the YTC has been impacted by wildfire, thereby converting shrub-steppe to grass-steppe, over the past 17 years (ENRD, 2004).

Relationships between military vehicle disturbances recorded along each transect and biological soil crust variables were confusing in this ordination because, in general, plots experiencing vehicle disturbance were present on the bottom and left side of the ordination, where several biological soil crust variables are shown to increase (see Figure 18; Tables 12 and 13). This relationship does not compare well with negative relationships between military training and biological soil crust discussed in chapter 2 (Watts, 1998). When comparing the ordinations of plots grouped by vehicle disturbance and plots grouped by wildfire, the supposition could be made that wildfire, and not

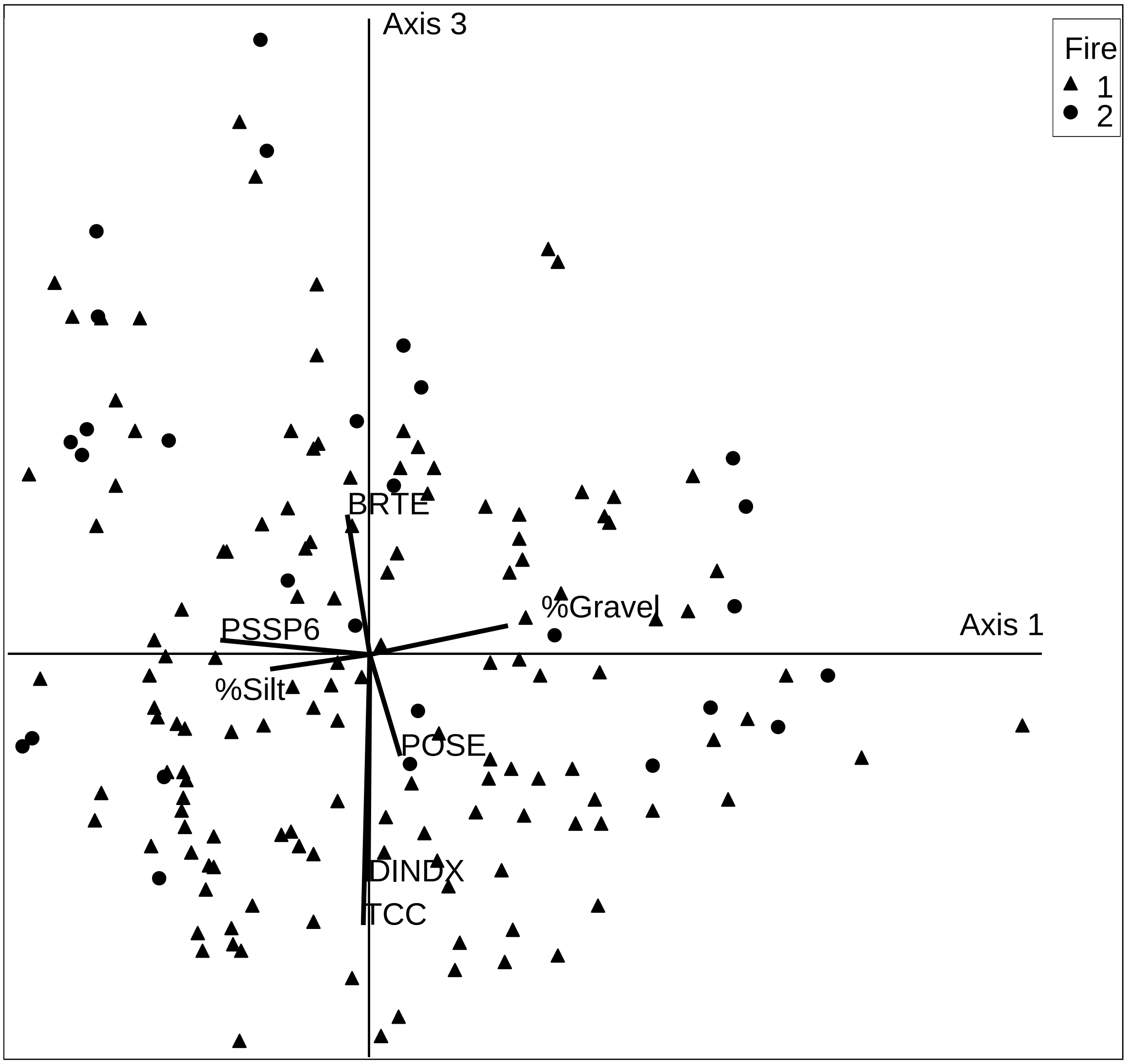

Figure 17. Nonmetric multidimensional scaling ordination of all plots read with the line intercept and point-line intercept techniques grouped by wildfire. 1 = no wildfire over the past 17 years; 2 = wildfire has occurred at the plot at least once over the past 17 years; BRTE = cheatgrass; PSSP6 = bluebunch wheatgrass; %Gravel = percentage of gravel; %Silt = percentage of silt; POSE = Sandberg's bluegrass; DINDX = dimensionality index; TCC = total crust cover.

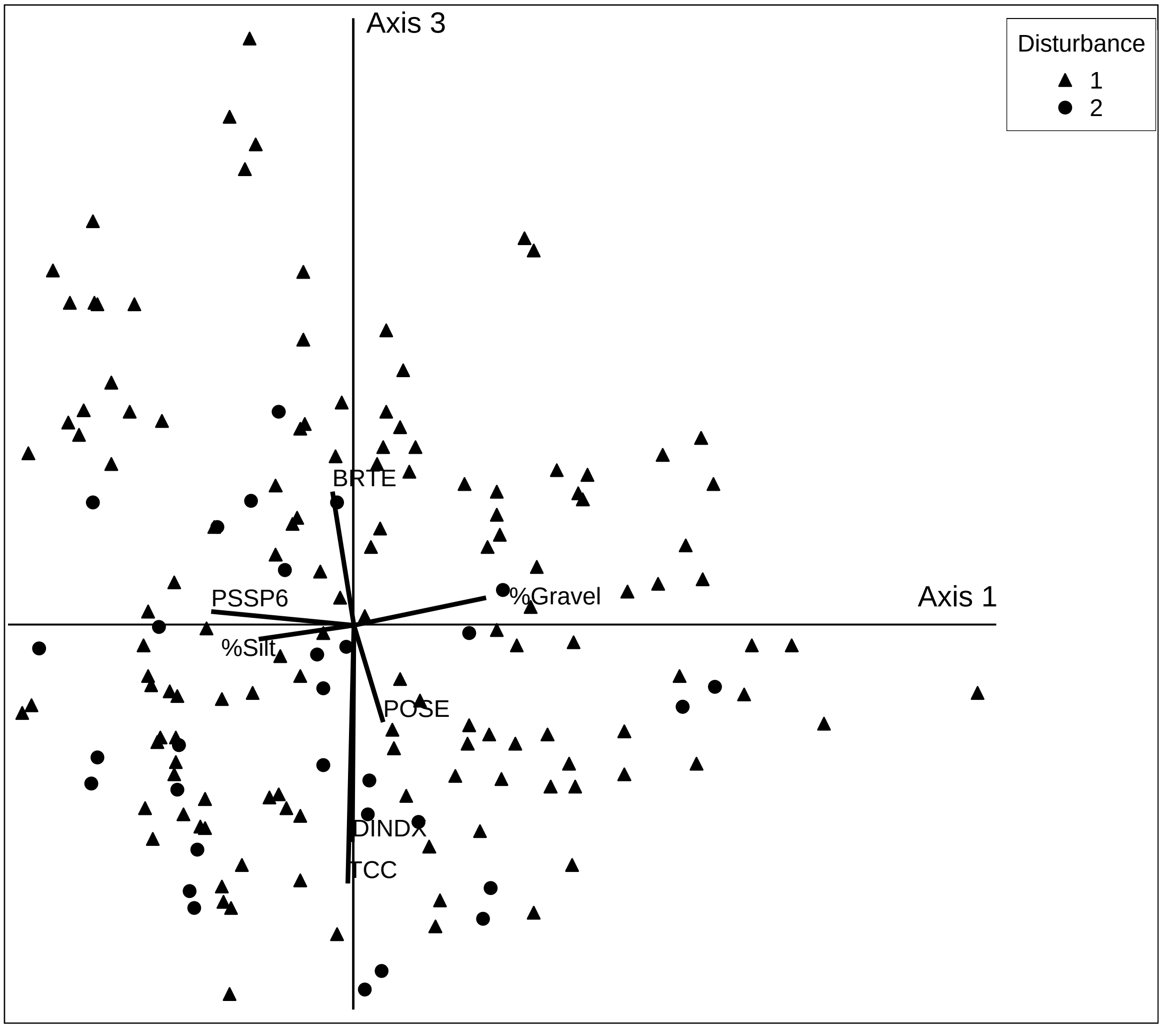

Figure 18. Nonmetric multidimensional scaling ordination of all plots read with the line intercept and point-line intercept techniques grouped by vehicle disturbance. 1 = no disturbance recorded during data collection efforts; 2 = disturbance recorded along the transect at least once during data collection efforts; BRTE = cheatgrass; PSSP6 = bluebunch wheatgrass; %Gravel = percentage of gravel; % Silt = percentage of silt; POSE = Sandberg's bluegrass; DINDX = dimensionality index; TCC = total crust cover.

vehicle disturbance, has the greatest impact on biological soil crust cover and composition at YTC. The ordination of plots grouped by vehicle disturbance does not take into account land use prior to initiation of LCTA plot monitoring, so results from this study can only suggest relationships with recently recorded disturbance data and not disturbances resulting from past land use. In addition, recent vehicle disturbance at grass-steppe plots may not have been visibly apparent during sampling efforts because of reseeding efforts or litter build-up from nonnative species covering vehicle tracks. Percentage of slope was included in the secondary matrix in hopes of explaining some of the relationships between past land use and current condition. However, percentage of slope was only slightly correlated with Axis 3 (Table 13), so these relationships were not observable with any level of certainty.

Taking into consideration MRBP and ISA, sampling techniques were significantly different, and the line intercept sampling technique was more useful in yielding significant indicators of habitat type and undisturbed plots. According to NMS, relationships between biological soil crust morphological groups and environmental variables, especially ground cover, soil texture, and vascular plants were equally apparent regardless of the sampling technique used. This observation is to be expected since datasets were collected along the same stretch of each transect. The differences noted between biological soil crust sampling techniques are most likely a function of the ability of line intercept sampling to capture a richer dataset, because, instead of capturing a minimal number of points along a line, it actually characterizes every centimeter along the line.

Regardless of the differences tested between sampling techniques, the greater amount of time and resources needed to conduct line intercept monitoring greatly out-weighs the benefit gained with this technique. In fact, each transect required approximately 15 min for point-line intercept sampling and 120 min for line intercept sampling. If the YTC were to implement one or the other of these techniques, they would likely read 200 points along the line or read 20 m of the line intercept technique. For temporal comparison, point-line intercept would require approximately 75 min per transect or 41 days to read all 262 transects, while line intercept would require 120 min per transect or 66 days to read 262 transects. If implementing the point-line intercept technique, the YTC could collect a greater number of points along each transect, possibly increasing the richness of the dataset, and would still conduct the sampling more rapidly than the line intercept technique. Therefore, the YTC should be able to effectively sample biological soil crust at all 262 core monitoring plots if using the point-line intercept technique.

Analysis of Biological Soil Crust and Environmental Variables

Biological soil crust variables, including morphological groups, the dimensionality index, and total crust cover, were combined with environmental variables, such as vascular plant species, ground cover, soil texture, pH, disturbance, elevation, and slope, in an attempt to determine the variable or groups of variables that provide the greatest amount of information for upland ecosystem monitoring. Statistical analysis of biological soil crust and environmental variables included NMS.

NMS results showed that the dimensionality index and total crust cover were aligned very closely, regardless of the habitat type or sampling technique, and were also closely aligned with tall moss (Figure 16; Tables 12 and 13). These relationships, along with tall moss being the most dominant morphological group (Table 4), suggest that total crust cover and the dimensionality index were tied closely to cover of tall moss. Yet, tall moss was but one of the morphological groups present along most transects. Several other morphological groups showed important relationships with various environmental variables.

A few morphological groups were selected as indicators of different habitat types and one morphological group was selected as an indicator of undisturbed plots. Tall moss and foliose lichen were selected as significant indicators of the dwarf shrub-steppe habitat type (Table 10). Squamulose lichen was selected as a significant indicator of the shrub-steppe habitat type (Table 10). Squamulose lichen was selected as a significant indicator of undisturbed plots (Table 11).

One specific relationship between total crust cover, the dimensionality index, and environmental variables was evident following NMS analysis. A gradient ranging from cheatgrass, Russian thistle, and litter to total crust cover, dimensionality index, crustose lichen, squamulose lichen, and tall moss was suggested on Axis 3 (Figure 16; Tables 12 and 13). However, another relationship suggested along Axis 1, where several morphological groups were present but aligned on opposite ends of the ordination, would not have been observed had total crust cover or dimensionality index been the only biological soil crust variables. This relationship along Axis 1 suggested a gradient ranging from fine-texture soil, bluebunch wheatgrass, big sagebrush, short moss, squamulose lichen, and litter to coarse-texture soil, stiff sagebrush, thymeleaf buckwheat, tall moss, and rock (Figure 16; Tables 12 and 13). Neither total crust cover or dimensionality index were positively or negatively correlated with Axis 1 (Table 13).

Taking into account the various relationships explained between morphological groups, total crust cover, the dimensionality index, and environmental variables in the NMS ordination, it is clear that morphological groups provided more information than total crust cover or dimensionality index. In terms of determining land condition or thresholds for military training loads, use of morphological groups for monitoring biological soil crusts will provide information about the composition of soil crusts that total crust cover and the dimensionality index may not provide. This is important because land use could possibly alter the composition of biological soil crust without altering the total crust cover. If biological soil crust monitoring can reveal changes in composition prior to overall decreases in total crust cover, then management actions can be recommended as to land use in a given area, thereby allowing biological soil crust to recover. Therefore, the YTC would benefit greatly, in terms of information provided by upland ecosystem monitoring, by utilizing morphological groups instead of total crust cover or the dimensionality index.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Baseline Biological Soil Crust Data

To summarize, baseline biological soil crust data were collected using morphological groups, dimensionality groups, and total crust cover. Representative biological soil crust voucher specimens were also collected along each transect. In addition, environmental variables such as vascular plant composition, ground cover, soil texture, soil chemistry, vehicle and fire disturbance, slope, and elevation were also recorded or obtained for each transect. These data were used to analyze the differences between biological soil crust sampling techniques and to determine which biological soil crust variables were most useful for YTC's upland ecosystem monitoring program. Biological soil crust data and voucher specimens can be used in greater detail to guide future monitoring efforts and to create an herbarium for verification of biological soil crust specimens encountered during monitoring.

Analysis of Biological Soil Crust Sampling Techniques

Statistical analysis including MRBP and ISA showed that the two sampling techniques were significantly different and some of the reasons why they were different. Even though line intercept and point-line intercept sampling techniques were significantly different and line intercept yielded more indicators of habitat type and undisturbed plots, these differences seem to be mostly related to the richness of the dataset for each sampling technique. In terms of efficiency, the point-line intercept technique would be more desirable because it was less time consuming to implement.

Additionally, sampling points along the entire 100-m transect would help to more adequately represent biological soil crust cover and possibly increasing the richness of the dataset when conducting upland ecosystem monitoring, and would still require considerably less time than the line intercept sampling technique. The only caution would be that point-line intercept along 100 m may not improve the richness of the dataset to a level equal to the richness of the line intercept dataset, so using point-line intercept may sacrifice richness of the dataset. This may be desirable for monitoring at the YTC because a greater amount of point-line intercept sampling can be conducted in less time than if using the line intercept sampling technique.

Analysis of Biological Soil Crust and Environmental Variables

Total crust cover and the dimensionality index were always aligned closely together in NMS ordinations. However, along Axis 1 a gradient in morphological groups from short moss and squamulose lichens to tall moss was evident without total crust cover and dimensionality index being correlated with the axis. Biological soil crust morphological groups were both successful in yielding indicators of various habitat types and undisturbed plots and explaining relationships between environmental variables and biological soil crust. Morphological groups are more desirable than total crust cover and dimensionality index because they are capable of providing information on changes to composition of soil crust that would not be as apparent using the other two variables. Future monitoring of biological soil crusts at the YTC should include the morphological groups utilized in this study, which would be most efficiently sampled by the point-line intercept technique across the entire 100-m length of LCTA transects.

This discussion of total crust cover and dimensionality index versus morphological groups leads to some interesting questions that were unanswered by this experiment. What other soil crust assessment methods or techniques may provide biological soil crust information to accompany LCTA monitoring? Would some combination of dimensionality groups and morphological groups be more useful (e.g., tall moss, short moss, two-dimensional lichen, and three-dimensional lichen)?

Recommendations for Future Biological Soil Crust Monitoring

YTC's upland ecosystem monitoring, LCTA, has recently been extensively altered. The new program is termed RTLA and is requiring all army installations to take a closer look at monitoring objectives, especially considering the effects of military training on training lands. The YTC is currently in the process of developing a protocol to fit RTLA guidance.

In the future, YTC's upland ecosystem monitoring will center on rapid qualitative monitoring over larger portions of the landscape as opposed to its current focus of more time consuming, quantitative monitoring efforts located at specific points on a relatively small percentage of the landscape. The expected monitoring protocol for upland ecosystems at the YTC will be very similar to the monitoring manual, *Interpreting Indicators of Rangeland Health* (Pellant, et al., 2005), cooperatively produced by representatives of the Bureau of Land Management, Natural Resources Conservation Service, U.S. Geological Survey, and Agricultural Research Service. YTC's protocol will be similar to this manual because it will utilize the same basic methodology, but will be altered to work for military training impacts as opposed to grazing land impacts.

Interpreting Indicators of Rangeland Health is a qualitative approach, often combined with quantitative or inventory data that might already exist, to evaluate various soil stability, hydrologic function, and biotic integrity indicators against reference conditions in an attempt to provide resource managers with a system for monitoring upland resources (Pellant et al., 2005). The YTC is planning to utilize existing quantitative data from LCTA and other monitoring efforts in conjunction with Natural Resources Conservation Service ecological site descriptions for YTC's major combinations of soil type and vegetation communities to develop reference conditions. For each of YTC's ecological sites, these reference conditions will be developed and used as the baseline potential conditions for future monitoring efforts. One of the many indicators of biotic integrity suggested by the rangeland health monitoring manual is biological soil crust cover.

Pellant et al. (2005) suggest that biological soil crusts might be included as an indicator of biotic integrity if "crusts play a particularly important biological or physical role" (p. 41). Based on literature review presented in this thesis, biological soil crusts likely do play a considerably important biological and physical role at the YTC. Therefore, biological soil crusts should be a measured and monitored attribute in YTC's future upland ecosystem monitoring program. Biological soil crust data obtained from this thesis should be used to determine reference conditions for the various ecological sites across the YTC. Once these reference conditions are determined, departure from those conditions can be evaluated, thereby yielding information about one of the many indicators of rangeland health at the YTC. Departure from reference conditions can be rated qualitatively with categories that include (a) none to slight, or largely intact biological soil crust that nearly matches the site capability; (b) slight to moderate, or biological soil crust is evident throughout the site but its continuity is broken; (c) moderate, or biological soil crust is present in protected areas and with a minor component elsewhere; (d) moderate to extreme, or biological soil crust is largely absent occurring mostly in protected areas; and (e) extreme to total, or biological soil crust is found only in protected areas and there is a very limited suite of morphological groups. These categories are an example of how to rate the departure of biological soil crust condition from reference conditions and some form similar to this should be used by the YTC. The categories and results from analysis of biological soil crust sampling techniques presented in this thesis may be useful to other land management agencies, such as the Bureau of Land Management, for developing quantitative and qualitative methods for sampling biological soil crust.

It is unlikely that biological soil crust data collected as part of this thesis will be sufficient for determining reference conditions for all of YTC's ecological sites. However, it should be used to aid in determining reference conditions for YTC's ecological site descriptions and can be supplemented with further biological soil crust data collection. The rangeland health monitoring manual suggests that qualitative monitoring efforts be validated with quantitative data (Pellant et al., 2005). Future biological soil crust quantitative data collection should follow these recommendations, using biological soil crust morphological group data collected with the more rapid point-line intercept technique (Table 15). The point-line intercept technique is also the suggested measurement technique for several indicators within all three of the rangeland health attributes, soil stability, hydrologic function, and biotic integrity (Pellant et al.). Biological soil crust voucher specimens collected as part of this thesis can be used for developing a moss and lichen herbarium collection, which will aid in training and identification during future monitoring efforts.

As a member of the RTLA protocol development committee, I have been involved in the process of developing the RTLA protocol by providing technical input. Given the importance of biological soil crusts in arid and semiarid environments and the work done on this thesis at the YTC, technical input about biological soil crusts will continue to be provided to YTC's natural resource managers, stressing the importance of including biological soil crust as a component of the RTLA protocol.

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