WEEDY BROME GRASSES AND THEIR POTENTIAL EFFECT ON THE INFILTRATION AND RECHARGE RATES IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-97-009

Prepared by

David P. Groeneveld
Randall W. Fedors
Stuart A. Stothoff

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

August 1999

ABSTRACT

Invasion by weedy plant species and replacement of the dominant shrub cover on Yucca Mountain (YM) and recharge zones of the Death Valley regional aquifer system may have a significant effect on the long-term integrity of the proposed high-level nuclear waste repository. The literature documents that regions where deep-rooted shrubs or trees have been replaced by relatively shallow-rooted grasses exhibit increased recharge, higher water tables, and greater streamflow. If the deep-rooted native shrubs within the catchment for the groundwater flow system beneath YM are displaced by invading grasses—a phenomenon apparently occurring across the western United States—annual transpiration rates will decline leading to increases in infiltration. Under current climatic conditions it is likely there may be significant increases in percolation fluxes through the repository horizon, and groundwater velocities may increase significantly in the saturated zone. Conversion from shrubs to grasses may greatly amplify the effect on site-scale and regional hydrology if the climate changes to cooler and wetter conditions.

Two weedy annual grass species, both members of the genus *Bromus*, are of special interest. Foxtail chess (*B. madritensis* ssp. *rubens* L.),[1] a Eurasian species that has become naturalized in warm deserts of western North America, has already invaded southern Nevada. Observations indicate that a permanent conversion from native shrub species to foxtail chess may be in progress over large areas that include the proposed repository. Cheatgrass (*B. tectorum* L.) although found only in restricted locations on YM and apparently less well adapted to the current arid climate of YM, may have a greater impact on repository performance by greatly increasing regional recharge at higher elevations, thereby increasing regional groundwater levels and groundwater velocities from the repository to the receptor locations. This species has begun to dominate rangelands across Nevada between 5,000 and 8,000 ft elevation. With future climatic changes to a pluvial environment at YM, cheatgrass invasion will become more likely.

The objective of this work is to assess the hydrologic effect of *Bromus* invasion in regard to the potential release of radionuclides from the repository, transport through the natural barriers encompassed by the unsaturated and saturated zones, and eventual exposure to a postulated critical group in the vicinity of YM. To assess the effect of brome grasses on site-scale and regional hydrology, ongoing work is being performed to (i) characterize the grasses sufficiently to perform infiltration modeling studies, (ii) determine the conditions under which brome grasses are likely to dominate, and (iii) perform consequence analyses accounting for increased net infiltration on site-scale and regional flow systems, both under current conditions and under conditions expected over a glacial cycle.

---

[1] Nomenclature according to Hickman, 1993.

CONTENTS

FIGURES

TABLE

Table | Page

ACKNOWLEDGMENTS

This work was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-97-009. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

This report was improved by thorough technical, programmatic, and editorial reviews provided by Amit Armstrong (CNWRA), David Cooper (Consultant), Budhi Sagar (CNWRA), and Barbara Long (CNWRA). The careful formatting of the document and preparing of tables by Roseanne Ard (CNWRA) and Paulette Houston (CNWRA) is greatly appreciated.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: Soil sample collection and measurements characterizing grain size distributions, noted in table 2-1of this report, have been recorded and described in scientific notebooks by the CNWRA authors following QAP-001. The grain size distribution measurements were done at the Utah State University Analytical Laboratories using standard procedures for sieving and hydrometer analysis. This laboratory, however, has not been reviewed by quality assurance auditors from CNWRA and, as such, the data is not qualified. No other CNWRA-generated original data are contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: No analyses are presented and no computer codes were used in this report.

1 INTRODUCTION

Performance assessments (PAs) of the high-level waste (HLW) repository proposed to be sited at Yucca Mountain (YM), Nevada, consistently identify both percolation fluxes passing through the repository horizon to the water table and groundwater fluxes in the regional aquifer as being critical factors in repository performance. Fluxes through the repository horizon determine both modeled radionuclide release rates and the velocities from the repository to the water table. Groundwater fluxes in the regional aquifer affect the travel time from the repository to the water table (the water table may rise or fall with changing fluxes) and the travel time from the repository footprint to receptor locations.

Fluxes in the unsaturated and saturated zones are dependent on net infiltration, which in turn is dependent on precipitation, evapotranspiration, and runoff. Replacement of native deep-rooted shrubs by shallow-rooted grasses would be expected to increase net infiltration by decreasing evapotranspiration. In large precipitation events, wetting pulses may penetrate to below the relatively shallow rooting zone of the grasses, which roughly corresponds to the zone where evaporation is effective. Based on water balance studies, deep-rooted shrubs are able to intercept most or all of the moisture otherwise escaping to depth as net infiltration, particularly in areas with deep soil such as the alluvial flats common across southern Nevada. For example, net infiltration in the deep alluvium in Frenchman Flat is estimated at 0.04 mm/yr (Conrad, 1993). Noting that there is no competitive advantage in possessing phenologically expensive deep roots unless significant moisture penetrates to depth, shrubs must tap soil zones recharged by precipitation that are well below the shallow depths noted for *Bromus* roots. Therefore, removal of deep-rooted shrubs or replacement with shallow-rooted grasses would be expected to significantly increase net infiltration. There is evidence that such replacement is currently occurring across western North America, and in the YM region in particular, due to the invasion of two Eurasian weedy *Bromus* species that have become naturalized in western North America. The dominance of *Bromus* species under cooler and wetter conditions associated with a return to a glacial cycle would increase percolation above the repository and increase recharge to the regional aquifer thus leading to water table rises both below the repository and along the flow paths from the repository to the Amargosa Desert.

Throughout this report, the word soil is used in the context of any unconsolidated sediments ranging from the thin colluvial layers mantling hillslopes to the thick alluvial sequences filling washes and valleys.

The implications of shrub replacement by annual grasses have not been addressed in the context of YM PAs. This report is intended to (i) document that shrub replacement appears to be occurring at YM and in the region, (ii) provide a synopsis of mechanisms for replacement, (iii) identify potential impacts on repository performance under current and forecasted cooler and wetter climate conditions, and (iv) describe ongoing and recommended studies to bound the effect of shrub replacement by annual grasses on percolation estimates over the repository and recharge estimates over saturated zone regional and site-scale model domains. A description of the current status and ecology of the two grass species is provided in chapter 2, while mechanisms employed for invasion and consequent shrub replacement are discussed in chapter 3. Implications of this vegetation conversion for repository performance are presented in chapter 4.

2 ECOLOGY OF BROME GRASSES

2.1 BACKGROUND

Two Eurasian grass species, foxtail chess, [*B. madritensis* ssp. *rubens* L. (also known as red chess)] and cheatgrass [*B. tectorum* L. (also known as downy chess)], are important invasive species that have become naturalized in western North America. And in many locations, they are rapidly increasing in population by replacing native perennials and grasses. Pictures of foxtail chess and cheatgrass are shown in figure 2-1, using specimens collected at YM. One effect of the seed morphology for both species that provides a mechanism for dispersal is demonstrated in figure 2-2.The ecological requirements for both brome species are similar, with the greatest difference between their preferred habitats being that foxtail chess favors warmer temperatures. Cheatgrass is more widespread in North America than foxtail chess, and thus has been considered to a greater extent in the literature; however, the similarity in their life history characteristics means that information about cheatgrass may largely apply to foxtail chess as well. For ecological measures including rooting depth, livestock palatability, phenology, proliferation, and takeover following range fires, foxtail chess and cheatgrass can probably be regarded as equivalent. Because foxtail chess occupies warmer, generally more arid habitats, this species probably has warmer cardinal temperatures for growth than cheatgrass.

Cheatgrass is increasing throughout large areas of Nevada, probably through a combination of factors including repeated burning, subtle climate change (increased annual variability of precipitation), and grazing (Young and Tipton, 1990) in addition to the intrinsic competitive ability and preadaptation that permits exploitation of the native flora's susceptibility to invasion (Mack, 1981). Alien annuals, especially cheatgrass, have been documented to reduce the reproduction of native perennials, and this tendency is enhanced under disturbances such as grazing (Harper et al., 1996).

Both brome species are relatively recent invaders to the region, in general, and to YM, in particular, and both are undergoing population explosions. In the Nevada Test Site (NTS) region, both species were first found in the 1930s, confined to disturbed areas in the Charleston Mountains (Clokey, 1951). Within the NTS, Beatley (1966) noted cheatgrass was absent or at densities less than 2 plant/m^2 below 4,000 ft and present at densities greater than 1,000 plant/m^2 on burned areas above 4,000 ft. This study assumed that the areas of weedy brome infestation were stable and not expanding. In 1987 and 1988 at the same sites, foxtail chess occurred at densities of 1,803 ± 474 plant/m^2 (below 4,000 ft) and 1,434 ± 304 plant/m^2 (above 4,000 ft), with cheatgrass found to be considerably patchier than foxtail chess and more strongly associated with the disturbed areas (Hunter, 1991). Although both species have affinity for disturbance, Hunter (1991) rejected a hypothesis that the increases in both species result from human activities, because the NTS has been protected from grazing, development, and recreation during the period of the invasion. In support of this conclusion, grazing, fires, and documentable human impacts did not occur on Anaho Island in Pyramid Lake, Nevada, during the period that cheatgrass invaded and replaced native perennial shrubs (Tausch et al., 1994).

Depending on location, cheatgrass may have no, promotional, or detrimental effects on rangeland use by livestock and native grazing species. Cheatgrass is useful as livestock feed if used during late winter through spring (Emmerich et al., 1993). Trammel and Butler (1995) found that grazing use by bison, elk, and deer was no different on cheatgrass and non-cheatgrass infested habitats. However, the forage value provided by cheatgrass is short lived while the loss of native species, especially because burning, may

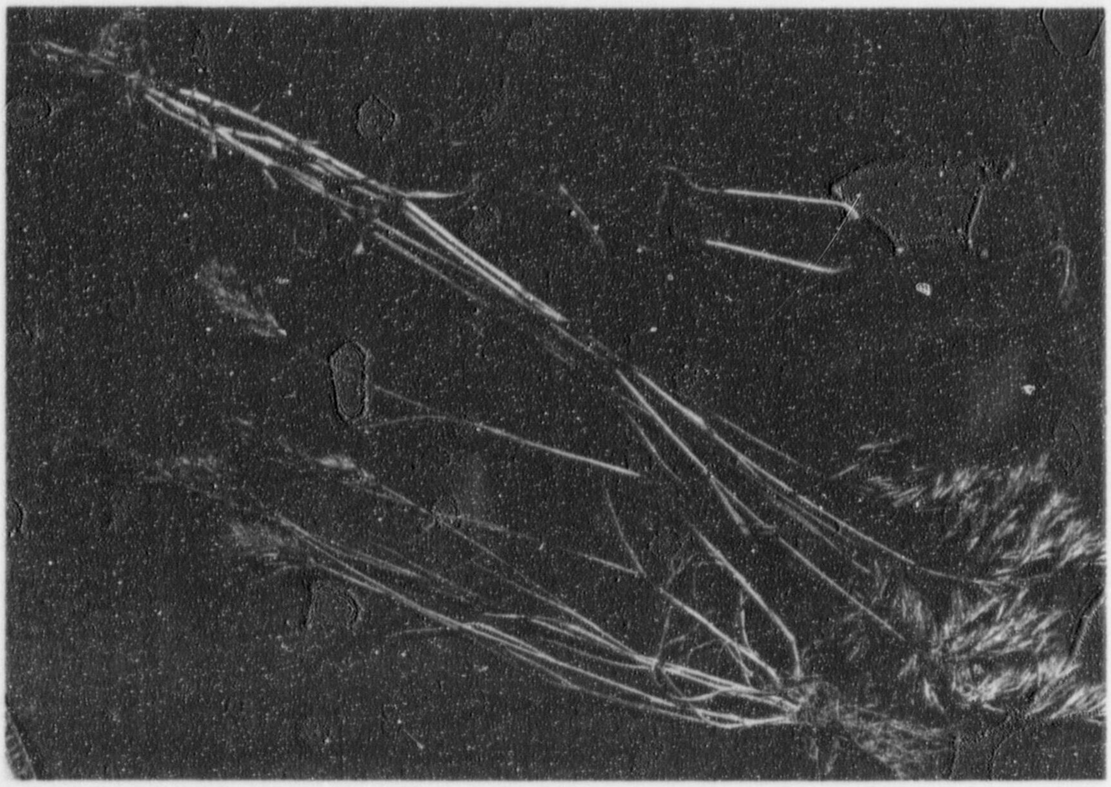

Figure 2-1. Cheatgrass (top) and foxtail (bottom) collected on Yucca Mountain

Figure 2-2. Cheatgrass and socks filled with cheatgrass seeds. The cheatgrass seeds tend to stick to animal fur, which provides a dispersal mechanism.

impact native ungulates. Replacement of native browse species, big sagebrush, and bitterbrush by cheatgrass on burned areas in northeastern California and northwest Nevada has resulted in a strong downward trend in numbers of deer using the range (Updike et al., 1990). Wildlife behavior also may exist that actually favors native vegetation over cheatgrass; for example, seed caching by rodents may control cheatgrass establishment and favor establishment of Indian ricegrass (McMurray et al., 1997). However, such mechanisms appear of minor consequence compared to fire ecology, fecundity, and the natural competitive ability of cheatgrass.

2.2 LIFE CYCLE

The two weedy brome grasses are winter annuals that germinate with the first fall rains, over winter as a basal rosette, and complete their life cycle during the spring (Klemmedson and Smith, 1964; Evans and Young, 1982). Dormancy of foxtail chess seed is maintained by warm temperatures that prevent premature germination following a summer thunder shower. After several months in dry soils, the seed is released from dormancy (Corbineau et al., 1992). Thus, intrinsic factors favor seed germination coinciding with the first rains of winter. Similar factors are likely for cheatgrass.

Winter activity by cheatgrass and foxtail chess is conferred through special adaptation. Root growth for these species is more tolerant of low temperatures than native grass species. For example, growth of cheatgrass can proceed until soil temperatures drop below 3°C, while root growth ceases in native wheatgrass when soil temperatures drop below 8–10 °C (Harris, 1967).

Cheatgrass has been found to maintain seed viability for one or more years. Such variable dormancy can buffer this plant from environmental perturbance such as wildfire or germination-producing precipitation followed by intensive drought that would destroy or severely decrease a population (Young et al., 1969; Young and Evans, 1976, 1978). In addition, this species maximizes seed production, which can induce carryover seedbed density of between 5,000 to 8,000 seeds/m^2 (Young et al., 1969; Young and Evans, 1975). These levels of seed reserves can lead to establishment of such heavy densities of seedlings [sometimes greater than 10,000 plant/m^2 (Young et al., 1969)] that germinating native perennial shrub seedlings are overwhelmed (Young and Evans, 1978).

The winter-annual nature of cheatgrass and foxtail chess confers additional competitive advantages over native vegetation. Because these species are active when soils are relatively moist, standard adaptive mechanisms for retarding water loss employed by native perennial species occupying the Mojave and other deserts, such as thickened epidermis and waxy coatings on leaves, thickened endodermis, and suberization of roots, are unnecessary. Released from these physiologically expensive requirements, cheatgrass can produce relatively large amounts of biomass, mostly in the form of reproductive structures and seeds (Hull, 1963). Growth is accomplished at a much greater water use efficiency than summer annuals (Hull, 1963), which probably results from growth and activity during late winter/early spring when the evaporative demand is relatively low (Harris, 1967). However, cheatgrass and foxtail chess must complete their life cycles quickly because the poorly suberized roots provide little protection against hot dry soil, resulting in ready plant desiccation (Harris, 1967; Thill et al., 1984). Such water deficit tends to induce early onset of maturation and reduce the seed set for cheatgrass, even though cheatgrass is considered to be drought tolerant (Richardson et al., 1989).

Blank et al. (1994) found that burned soils have a promotional effect on cheatgrass over unburned soils. This relationship is not well understood and reasons that cheatgrass may occupy one microsite versus another, for example occupying the zones beneath former tree canopies on a burn, are difficult to explain using commonly measured soil variables (Tausch et al., 1995). Cheatgrass is apparently an intense sink for soil nitrogen, as indicated by reductions in assimilated nitrogen content in plants growing on sites where water is readily available compared to sites where soil water contents are reduced (Rickard, 1985). Perhaps burning returns some of the nitrogen to the soil.

Cheatgrass has been shown to have genetic plasticity that permits environmental selection that may optimize germination requirements to micro-environments (Beckstead et al., 1996; Meyer et al., 1997). Especially after a fire, large fluctuations in population size have the potential to produce a new population that is fitted to microsite ecological conditions (Young and Evans, 1985). This genetic plasticity probably exists as well for foxtail chess but is not reported in the literature. Ultimately, genetic plasticity may permit these brome grasses to adapt to a wide variety of habitats through southern Nevada up to some upper elevational limit, with foxtail chess typically dominating at lower elevations and cheatgrass at higher elevations.

2.3 ECOLOGICAL FACTORS AS GUIDANCE FOR INFILTRATION MODELING

Cheatgrass has a finely divided root system that can penetrate to depths of 33 cm (Klemmedson and Smith, 1964), at least 80 cm (Cline et al., 1977), and, under some circumstances, as deep as 150 cm (Hulbert, 1955). Most of cheatgrass roots excavated on YM and elsewhere were observed shallower than 40 cm. At Lida Pass, Nevada, a cheatgrass ecotone was cursorily investigated for rooting depths and to ascertain whether soil textures or other readily observable factors are responsible for the ecotone. No evidence of fire was present at this site. Pictures of the site investigation are shown in figures 2-3 and 2-4. Four locations were investigated, one on the north side of State Route 266 in the middle of a large cheatgrass zone, one on the south side of State Route 266 in the middle of the cheatgrass ecotone, and in two locations bracketing the ecotone. Soil textures are presented in table 2-1, with quite similar sandy loam textures and rock content at each location. The soil textures are similar to those measured at YM (Schmidt, 1989). Cheatgrass roots were generally absent below 40 cm (16 in). No noticeable difference of soils, native vegetation, or recent burning existed from within the cheatgrass growth to the zone below the cheatgrass. Accordingly, the spread of cheatgrass appears to be in progress and the ecotone is only a temporary artifact of this process. The heavy near-surface proliferation of roots allows extraction of all available water in this zone during the growth cycle (Harris, 1967).

Fayer and Jones (1990) provide guidance on calculating cheatgrass transpiration in the context of demonstrating model usage for the one-dimensional (1D) simulator, UNSAT-H. Field experiments at the Arid Lands Ecology Reserve in the Hanford Washington Site (Hinds, 1975) found that 63, 81, and 88 percent of cheatgrass root biomass is in the top 10, 20 and 30 cm of the soil column at the end of the growing season. Based on these observations, Fayer and Jones (1990) describe root zone biomass using a small constant value plus an exponential function with an extinction depth (the depth at which biomass decreases to 1/e times the surface density) of 7.75 cm. At the same site, the native bluebunch wheatgrass species had a much more gradual decline in biomass with depth. Fayer and Jones (1990) suggest that transpiration be characterized using a ratio between potential transpiration and net radiation, with the ratio increasing linearly from 0 at the beginning of October to 0.3 in early April, maintaining steady throughout May, and linearly dropping to 0 through June. Actual plant uptake is modeled as proportional to root-length density and soil moisture, as well as net radiation. Fayer and Jones (1990) make no attempt to account for root growth. They note that the

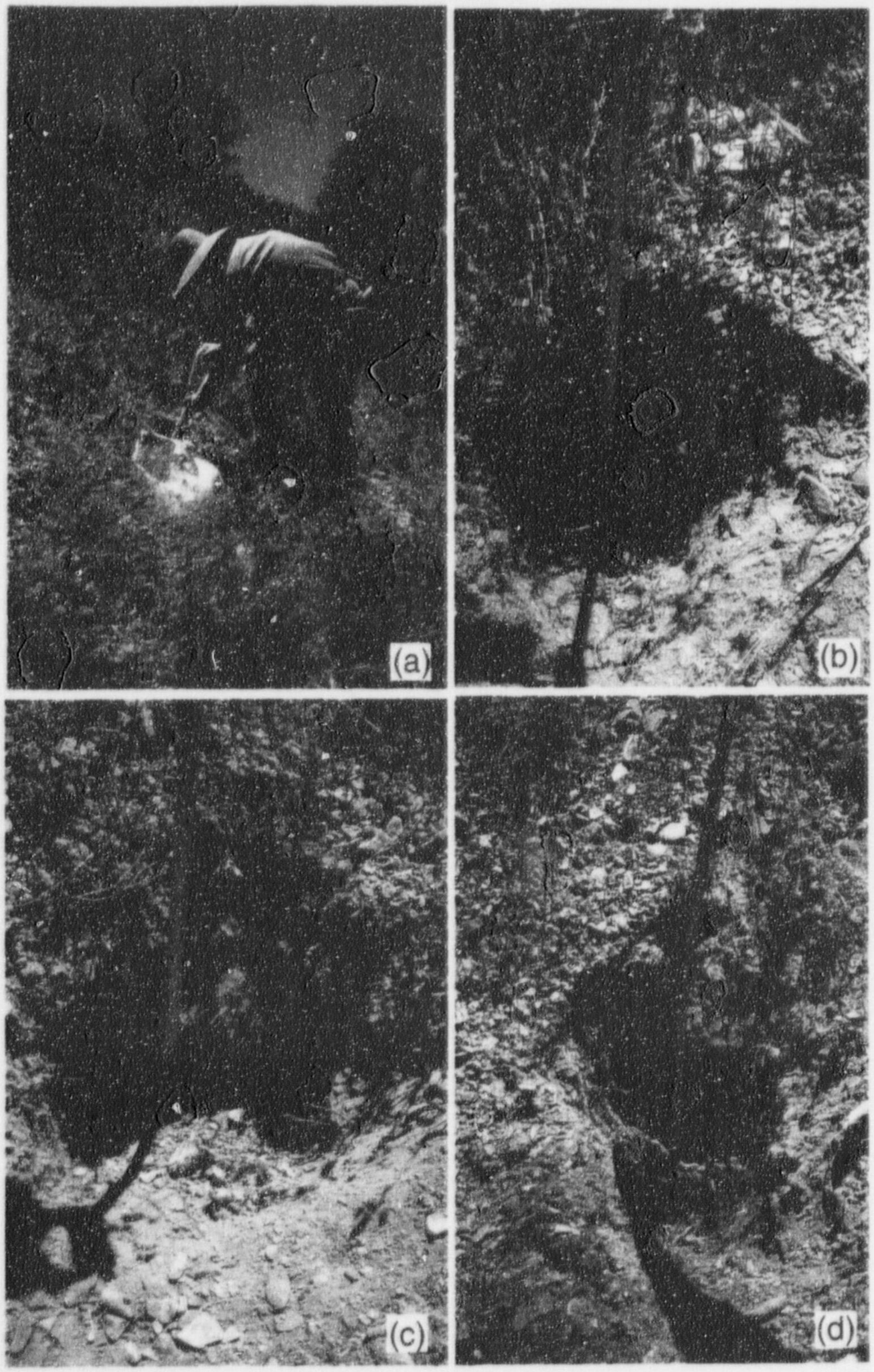

Figure 2-3. Soil pits dug near Lida Pass, Nevada, as shown in figure 2-4 (a) at the cheatgrass ecotone, (b) within the cheatgrass cover and above the ecotone, (c) at the ecotone, and (d) below the ecotone and outside the cheatgrass cover. All pits had a sandy loam texture (table 2-1) with no noticeable difference of soils, native vegetation, or previous burns from within the cheatgrass growth to outside the ecotone.

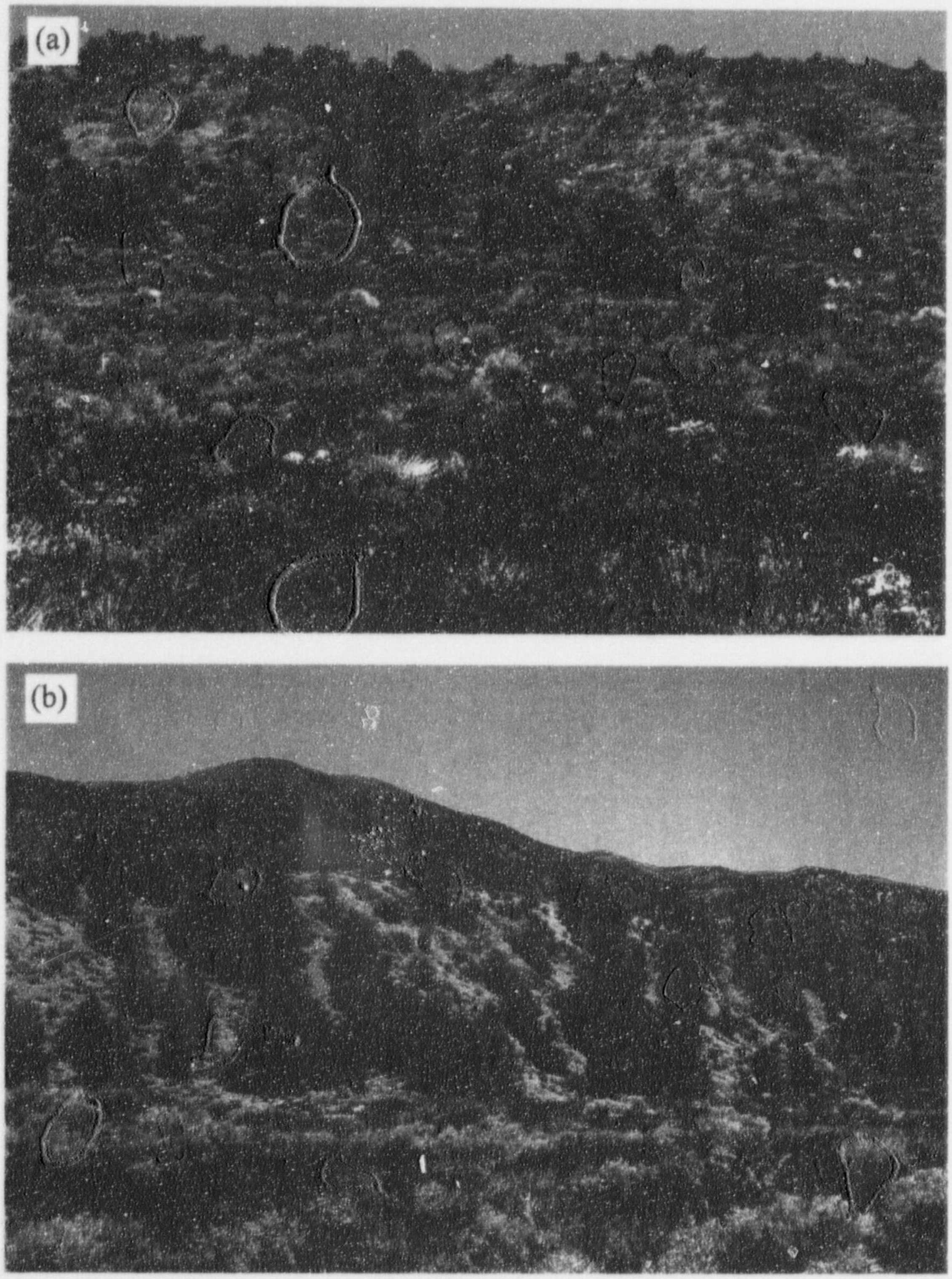

Figure 2-4. Investigation site along State Route 266 at Lida Pass, Nevada, south of Tonopah at about 7,000 ft elevation. Cheatgrass is the reddish grass visible between shrub crowns. (a) The north side of the road. (b) A terrace immediately on the other side of the road where the ecotone between a cheatgrass patch and surrounding vegetation was investigated. The soil pits pictured in figure 2-3 are from this location.

Table 2-1. Soil samples obtained at Lida Pass, Nevada, located approximately 80 m northwest of Yucca Mountain. The sample obtained opposite the ecotone corresponds to figure 2-4, and the samples above, in, and below the ecotone correspond to figures 2-4 and 2-3a-d.

Location	Depth (cm)	>2 mm (percent)	Sand (percent)	Silt (percent)	Clay (percent)
Opposite ecotone	0 to 14	67	57	35	8
	14 to 40	74	59	29	12
Above ecotone	0 to 30	69	69	20	11
	30 to 50	72	64	22	14
In ecotone	0 to 30	60	69	22	9
	30 to 40	76	67	19	14
Below ecotone	0 to 7	69	69	21	10
	30 to 50	72	69	20	11

relationship between plant biomass and transpiration has not been determined, suggesting that a direct proportionality be used. Note that deep roots may be relatively more efficient than shallow roots at extracting soil water because the proportion of the root biomass devoted to transporting water increases upward.

3 INVASION OF BROME GRASSES

3.1 FIRE AND PESTILENCE

Fire figures prominently in the large-scale replacement of native vegetation by cheatgrass and foxtail chess. Cheatgrass matures earlier than native species, dries during early summer to provide fuels that can readily carry wildfire, and increases the likelihood of repeated wildfires (Young et al., 1987). These factors greatly increase wildfire frequency and extent. For example, fire frequency in lands formerly vegetated by sagebrush steppe increased from once in 60–110 yr to intervals of less than 5 yr due to dominance by cheatgrass (Whisenant, 1990). Cheatgrass has become sufficiently abundant to provide fuel for extensive and disastrous range fires in the Great Basin (Billings, 1994). Similar trends exist for foxtail chess. For example, Brown and Minnich (1986) found that stands formerly dominated by creosote bush and bursage, once burned, were replaced with plant cover dominated by annual species, especially foxtail chess. Due to the increased ability for such weed-invaded sites to carry fire, such trends are likely to become reinforced. Similar replacement of blackbrush by brome grasses may be happening in areas of the NTS where target practice has caused fires, such as areas near Shoshone Mountain (see figure 3-1).

Brome grasses also provide a mechanism for native parasitic vegetation to attack native shrubs. In 2 of the past 5 yr, the authors observed infestations of dodder (*Cuscuta denticulata* Engelm) in Amargosa Valley, just south of the NTS. Dodder is highly recognizable during portions of its life cycle, looking like orange "silly string" sprayed over the vegetation (see figure 3-2). Dodder attacks and kills a shrub by girdling the shrub's branches while extracting water and nutrients through vascular tissue that invades the host branches. Without grasses, the natural shrub spacing is far enough apart to limit infestation; however, a dense growth of grasses between shrubs provides a ready highway for dodder to cross from shrub to shrub. Creation of a pathway for native parasitic vegetation is less important than fire as a mechanism for eradicating native shrubs, because fire may induce a relatively complete kill of native shrubs over much larger patches.

3.2 PHENOLOGY

Although agents such as fire, grazing, and even drought may hasten the invasion and takeover by these weedy brome grasses, there is evidence that such disturbance may not be necessary for these species to establish dominance. For example, cheatgrass apparently can invade and replace stands of native shrubs without human-caused disturbance or fire as has been demonstrated on Anaho Island in Pyramid Lake, Nevada: grazing, fires, and human-induced disturbance have not occurred on this island during the period that cheatgrass invaded and replaced native perennial shrubs (Tausch et al., 1994).

The phenology of cheatgrass and foxtail chess confers distinct advantages over the native species: these brome grasses are in the greatest phase of growth, depleting the shallow soil zone of moisture and nutrients, precisely when native species are undergoing the precarious process of germination and seedling establishment. The key to this cycle is fall germination and slow growth through winter when native species may be dormant. Further, the winter cycle enables brome grasses to dispense with phenologically expensive mechanisms for minimizing water loss, enabling relatively profuse seed production that can yield seedling densities greater than 10,000 plant/m^2 (Young et al., 1969).

Figure 3-1. Invasion of brome grasses in a burn near Shoshone Mountain in the Nevada Test Site. The golden areas are dominated by cheatgrass with some rabbitbrush. Dark areas are the native blackbrush.

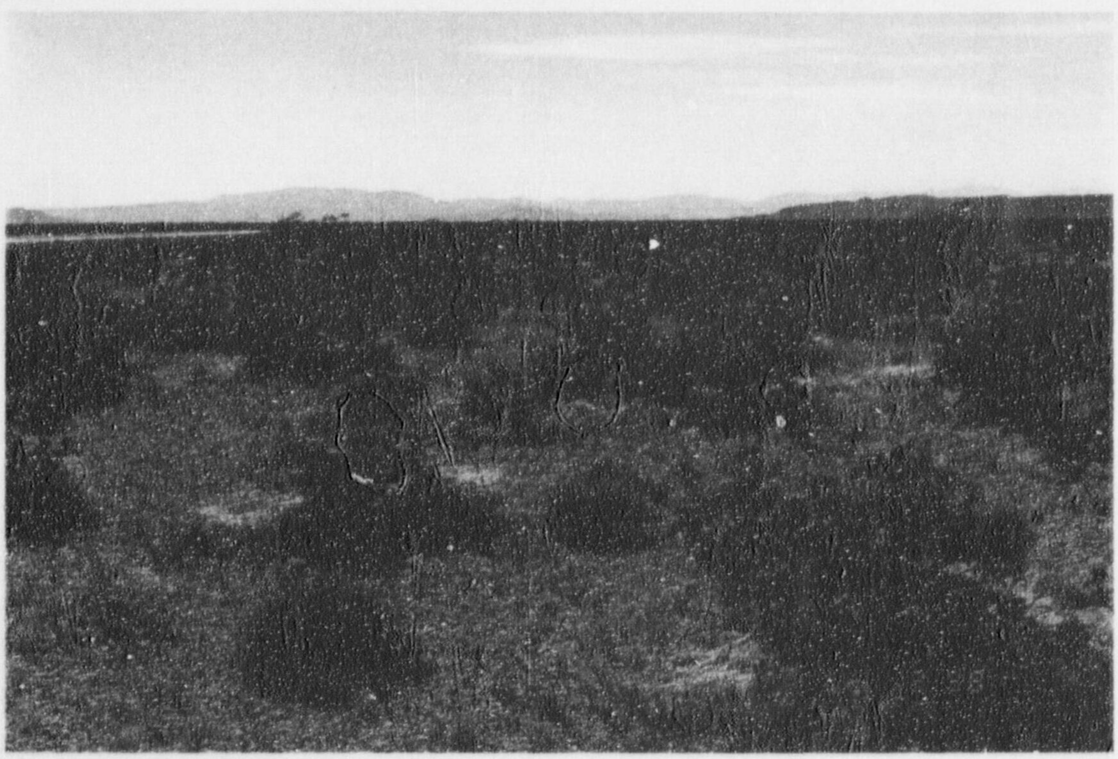

Figure 3-2. Dodder infestation in Amargosa Valley, with shrub-to-shrub transfer abetted by a carpet of foxtail chess and another annual introduced weedy grass, *Vulpia octofloro (Walter) Rydb.*

Cheatgrass competition for water and nutrients reduces the growth of native grass and shrubs even at 12 yr following the fire that permitted its establishment; this competitive ability enhances exploitation of soil resources within plant communities formed of native species (Melgoza et al., 1990). Additionally, cheatgrass is apparently an intensive sink for soil nitrogen, as indicated by reductions in assimilated nitrogen content in plants growing on sites where water is readily available compared to sites where soil water contents are reduced (Rickard, 1985).

Completion of the growth cycle in spring, earlier than native grasses, was found to confer competitive advantage of cheatgrass against the native grass *Agropyron spicatum*, which is only beginning its growth cycle during this period (Harris, 1967). The effects of rapid root growth, including depletion of near-surface soil water, were found to provide a strong competitive advantage against *Agropyron cristatum*, which initially experienced high germination rates but whose seedlings later succumbed to water stress within an established stand of cheatgrass (Stewart and Hull, 1949).

The same mechanisms used by brome grasses to compete with native grasses may be used to compete with seedlings of native shrub species, that are more vulnerable than fully established deep-rooted shrubs occupying a different ecological niche. Such competition may be preventing recruitment of native shrubs to replace those that succumb to old age or other causes in southern Nevada, in general, and YM, in particular. Areas where shrubs died during the drought period 1989–1991 (Schultz and Ostler, 1995) have been noted by these authors to show virtually no recruitment of shrubs during the wetter years that have occurred since that time. On these sites, the brittle carcasses of shrubs can still be seen while the growth of foxtail chess apparently surpasses 1,000 plant/m^2 (see photographs in figures 3-3a, Abandoned Wash, and 3-3b, just south of Highway Ridge, both at 4,000 ft elevation on YM). In the absence of fire, shrubs that can reproduce through cloning may be more likely to avoid germination pressures and, thus, be able to compete with brome grasses.

Based on these observations, the most cogent model for the replacement of native perennial species is that the intensive competition for water and nutrients during the vulnerable germination and seedling phases of the native species tends to prevent seedling establishment. Thus, even though established shrubs may easily coexist with brome grasses, complete disappearance of shrubs may occur within as short a period as the lifespan of a typical shrub (30–100 yr). At heavy infestation rates well in excess of 1,000 plants/m^2 (Hunter, 1991), these weedy species may be bringing recruitment of perennial plants to an abrupt end over large areas of southern Nevada. Increased fire-frequency rates in the presence of brome grasses may only serve to speed this replacement.

3.3 OBSERVATIONS OF BROME INFESTATION

The invasion of brome grasses in western United States has been documented extensively in the literature (Stewart and Hull, 1949; Harper et al., 1996; Mack, 1981; and Young et al., 1987). Based on observations, the invasion of *Bromus* is also occurring in southern Nevada. Several locations in southern Nevada and western Utah were identified where *Bromus* is currently invading native shrub steppe. As shown in figure 3-3, foxtail chess is active at YM, at about 4,000 ft elevation. Other sites have heavy cheatgrass infestation up to 8,000 ft elevation. Pictures of the sites, from east to west, are shown in figure 3-4 (7,000–8,000 ft, Paradise Mountains, western Utah); figure 3-5 (7,500 ft, Quinn Canyon Range, Nevada); figure 3-6 (6,000 ft, Reveille Valley, Nevada); figure 3-7 (6,000 ft, Saulsbury Summit, east of Tonopah, Nevada); figure 3-8 (6,000 ft, McKinney Tanks Summit, east of Tonopah, Nevada); and figure 2-4 at the site

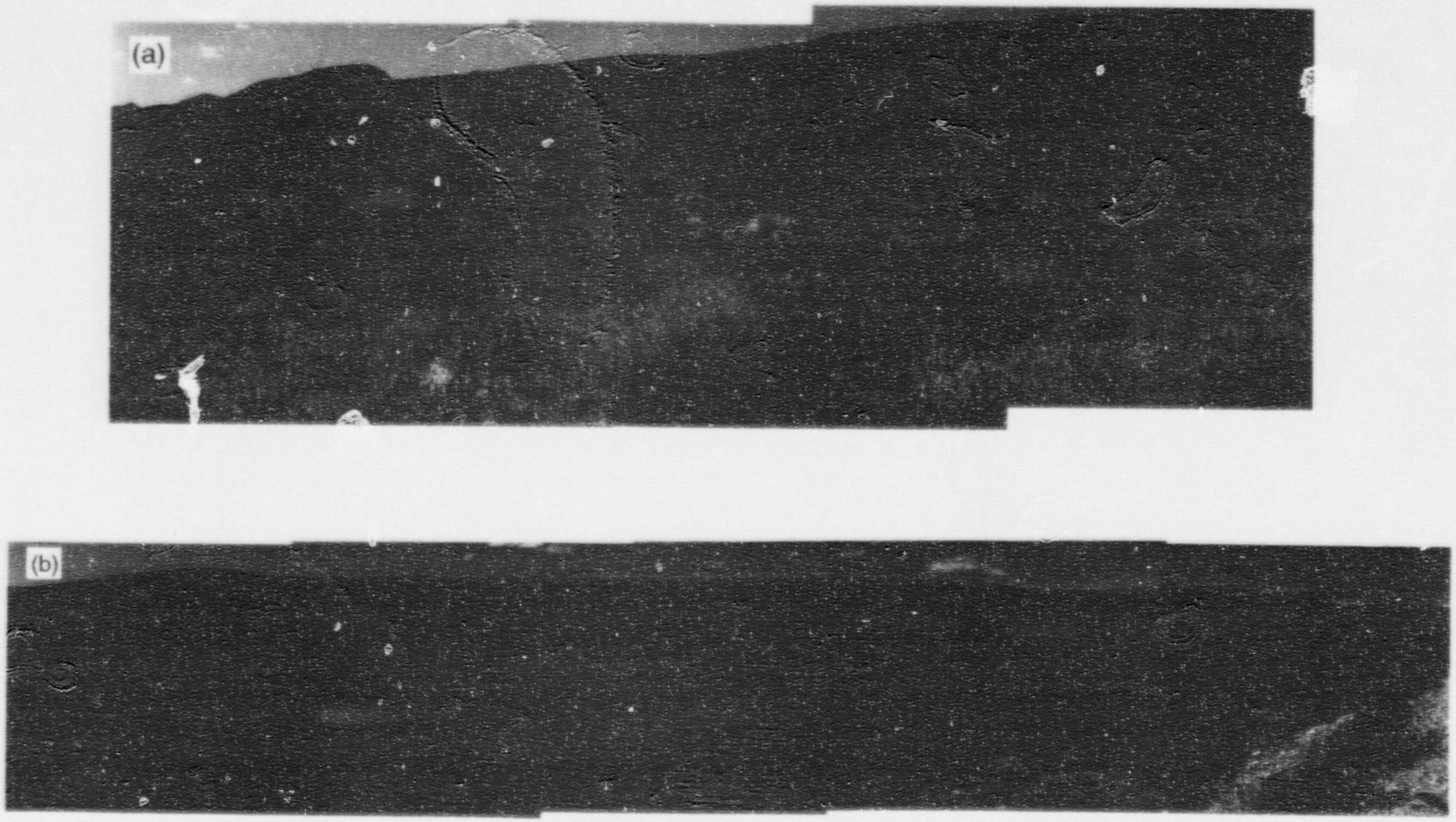

Figure 3-3. Photomosaics of foxtail chess growing on Yucca Mountain. (a) At the base of Abandoned Wash, perennial shrubs are interspersed with foxtail chess with almost no shrub recruitment. (b) Just south of Highway Ridge, the drought-prone areas have low shrub cover (some areas with less than 5 percent cover), heavy foxtail chess infestation, and shrub carcasses from the 1989–1991 drought.

Figure 3-4. A burn between 7,000 and 8,000 ft elevation in the Paradise Mountains in Utah, just over the Nevada-Utah state line. The reddish color is cheatgrass-dominated vegetation. The burn is probably between 3 and 5 yr old.

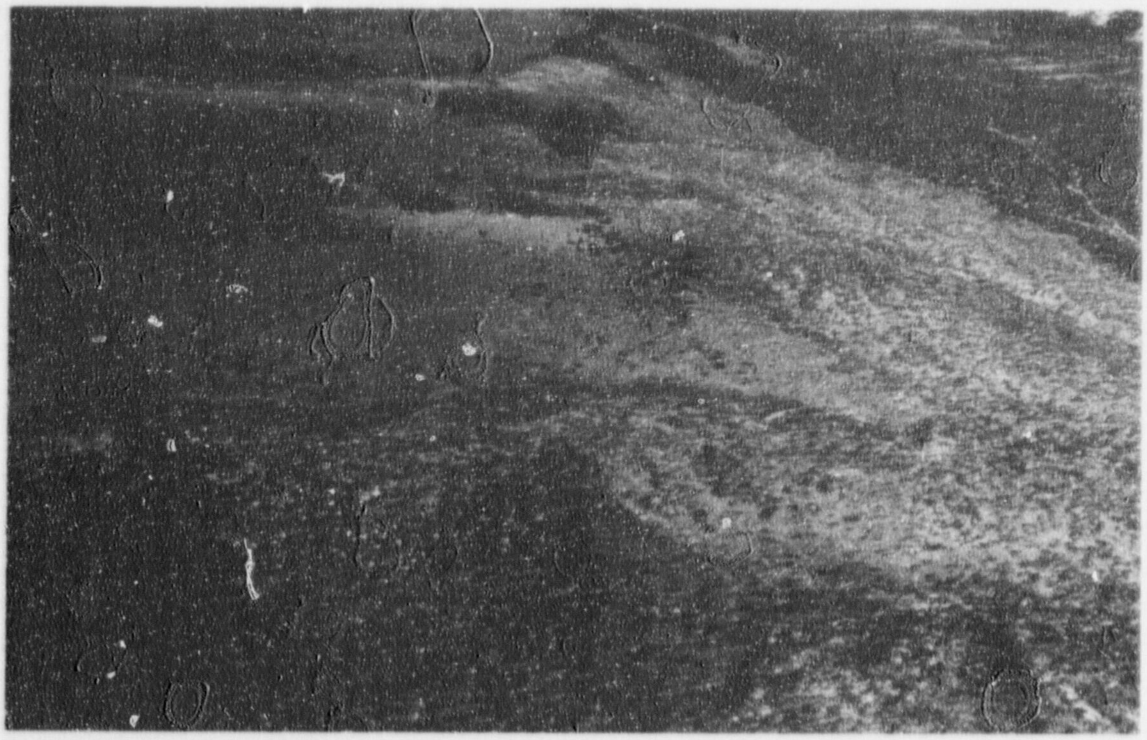

Figure 3-5. A burn at approximately 7,500 ft elevation in the Quinn Canyon Range, Nevada, north of Nellis Air Force Base. Cheatgrass (reddish color) has become dominant on portions of the burn. The burn is approximately 5 yr old.

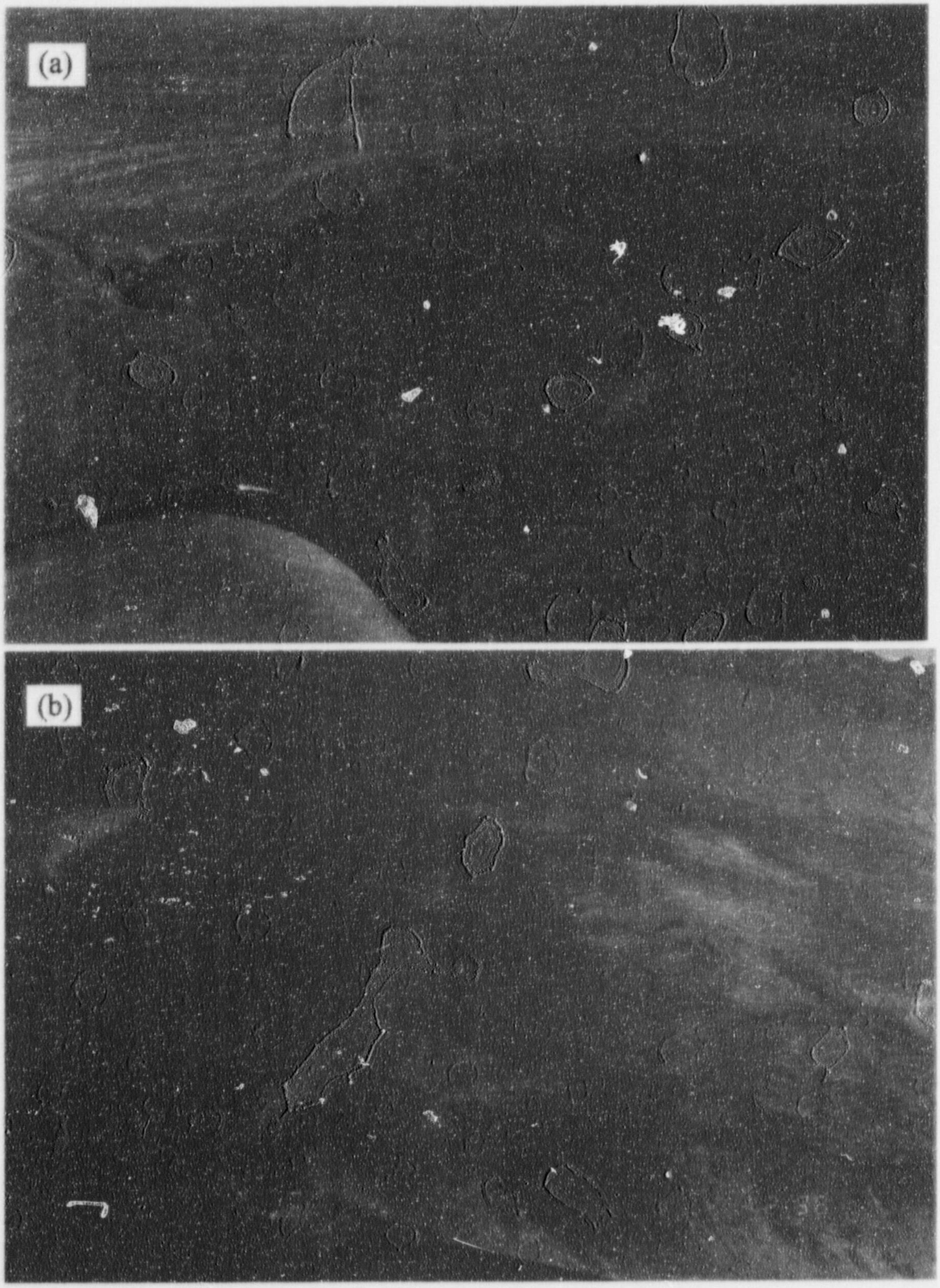

Figure 3-6. Two views (a) and (b) of Reveille Valley, Nevada, slightly west of Quinn Canyon Range. The elevation is approximately 6,000 ft. Spreading patches of cheatgrass are visible as a light reddish brown color among the sage green cover of shrub canopies.

Figure 3-7. Photomosaic of the south-facing side of U.S. Highway 6 at Saulsbury Summit, east of Tonopah, Nevada, at about 6,000 ft elevation. Infestation of cheatgrass coincides with low density of shrubs where cover was lost in the 1989–1991 drought.

Figure 3-8. Photomosaic of U.S. Highway 6 at McKinney Tanks Summit east of Tonopah, Nevada, at about 6,000 ft elevation. Cheatgrass infestation (purplish among native shrub cover) areas have less shrub cover than non infested areas.

of the soil excavation described in chapter 2 (7,000 ft, Lida Pass, Nevada). The significance of the elevations given here is that plant communities at present-day sites in southern Nevada, but higher elevations than YM, can be studied as future climate analog for YM due to decreases in temperature with increases in elevation.

Brome grass invasion has also been documented on the NTS and on YM. Hunter (1991) identified a trend of increasing infestation over the past 20–40 yr on the NTS. Although bromus grass is widespread, no data are available to evaluate whether *Bromus* is increasing at YM. The prevalence of foxtail chess on the YM block has been characterized by Rasmuson et al. (1999). Their study of eight sites on the eastern flank of YM determined that foxtail chess was the only plant species that covered more than 10 percent of any of the study plots, ranging from 6 to 23 percent. No other species that covered more than 1 percent of any site was found at all sites. The grasses, when grouped together, covered an average 17 percent of the area whereas shrubs covered an average 10 percent and forbs 11 percent of the area.

3.4 IMPLICATIONS FOR REPLACEMENT OF NATIVE PLANTS IN THE YUCCA MOUNTAIN REGION BY WEEDY BROMES

Controls on growth and dominance have not been fully established for these species. Upper elevational limits for these species are expected, as these species most often function as winter annuals whose root systems cannot grow at soil temperatures below 3 °C [measured for cheatgrass (Harris, 1967)]. Where cool winter temperatures reduce cheatgrass success, competition with native species may further reduce the importance of this plant. For example, in a comparison of modern vegetation with that recorded during boundary surveys in Skull Valley, Utah, juniper (*J. osteosperma*) apparently competed well with cheatgrass. While at lower elevations, sagebrush and shadscale dominated sites, cheatgrass has become dominant (Sparks et al., 1990). As seen in figures 3-4 and 3-5, however, cheatgrass may successfully compete (at least in disturbed areas) at elevations up to 8,000 ft where mean annual temperature (MAT) may be 7–10°C cooler than at the base of YM. Similar reductions in MAT are typically used as analogs for full glacial maximum conditions in PAs.

Deep alluvial soils are ideal habitat for brome grasses. In areas with deep alluvium, it is quite possible that foxtail chess will replace native shrubs at lower elevations and cheatgrass at higher elevations. In areas where soil is thin to nonexistent, brome grass must be sparser than in deep alluvium. Thus, *Bromus*-amplified fire frequency may be less of a threat to native species; however, the usual mechanisms for stifling recruitment of native perennials are also active in shallow soils. Species that reproduce by cloning (e.g., Ephedra *viridis*) may be able to successfully compete in shallow soils. The dense cover of foxtail chess in shallow soils on YM ridges and sideslopes, with apparent suppression of shrub recruitment in drought-prone regions (e.g., south-facing slopes with shallow soil cover), suggests that brome grasses may also compete successfully where soils are less than 10–20 cm (4–8 in) in thickness. Lower soil-thickness limits for successful brome-grass competition have not been established.

Based on the observations at higher elevations, it is likely that cheatgrass will compete well with native species if climatic change results in cooler and wetter conditions. This, of course, assumes that conditions are not so cold that cheatgrass seedling survival during winter and early spring is inhibited. Cheatgrass is currently growing on south-facing roadcuts above 9,000 ft elevation in Colorado under climatic conditions far cooler and wetter than would exist at YM under forecasted full glacial maximum. Thus, it is unlikely that climatic change will prohibit regional growth of cheatgrass.

Under monsoonal conditions (warm, with summer storms), such as experienced at roughly 12–9 ka, cacti dominated the Amargosa Valley with significant presence of grasses (Spaulding and Graumlich, 1986; Bull, 1991). Net infiltration under monsoonal conditions would likely be less than present for locations today with corresponding mean annual precipitation (MAP) and MAT, due to the increased effectiveness of evapotranspiration resulting from the change in precipitation seasonality from winter to summer dominance. The potential for foxtail chess to dominate under monsoonal conditions, such as exist in the Sonoran Desert, has not been ascertained. The summer rainfall patterns of a monsoonal climate are not well matched to the winter-annual behavior of weedy annual brome grasses; however, these species could compete at higher elevations under monsoonal conditions and would be expected to reinvade once monsoonal conditions cease.

Elevational limits and related factors such as aspect, soil thickness, and interspecies competition are presently not well understood for the brome grasses, especially for developing realistic projections of vegetation cover over a glacial cycle. The works of Rasmuson et al. (1999) could be taken in the context of climate-induced changes to infiltration. Rasmuson et al. (1999) estimated a 30 percent increase would occur in brome grass cover at the expense of shrub cover over the repository footprint due to the thermal pulse-induced increase in soil temperature and corresponding increase in water stress for the shrubs. Their conclusions were based on eight field plots covering a natural thermal gradient on the east flank of YM.

The approximately 50,000-yr packrat midden record from Fortymile Canyon near YM documents vegetation assemblages that range from species present during today's climate to species that occurred during glacial conditions (Spaulding, 1994). With the exception of white fir and limber pine that were present but not dominant about 16,000 yr before today, all of the plant species noted, including pinyon and juniper, have been documented susceptible to conversion to cheatgrass cover through agencies of fire, phenology, and competitive ability as discussed previously.

4 HYDROLOGIC IMPLICATIONS OF BROME DOMINANCE FOR REPOSITORY PERFORMANCE

The interplay of precipitation, temperature, and plants on a seasonal basis is an important factor for controlling infiltration and recharge. Based on precipitation summaries of meteorological stations in the YM region (CRWMS M&O, 1998), precipitation intensity is commonly high during August and November through March for 1-hr data. November through March is also a period of longer duration storms and more days with rain. El Niño events appear to have their greatest impact during winter months and may, in fact, play a large part in the onset of periods of infiltration that percolate to depth. Evaporation and transpiration potentials generally decrease during the winter months because of lower temperatures and plant dormancy. At Rainier Mesa, a high elevation recharge zone, the water percolating at depth carries a stable isotope data signature characteristic of winter precipitation (Russell et al., 1987). In the deep alluvial basins, which are generally lower elevation areas, water balance studies indicate there is little recharge except in stream channels during large storm events (CRWMS M&O, 1998). Any change in the seasonality of plants and the way that water is extracted from the soil, such as shrub replacement by *Bromus*, has the potential to modify the infiltration rate near the surface and also the percolation rate at depth.

4.1 DIRECT INFLUENCES ON NET INFILTRATION AND RECHARGE

Numerous scientific studies have shown that changes in vegetation cover may alter basinwide water yields (Bosch and Hewlett, 1982). Decrease of vegetation cover has been found to induce rising water tables (Peck and Williamson, 1987). Profound effects on runoff (>3-fold increase) and water tables (rise of 2.3 m/yr) have been found from basins where vegetation cover was reduced by only 53 percent (Ruprecht and Schofield, 1991a, b). Analysis of streamflow in a basin where vegetation conversion from trees (eucalyptus) to meadow (grass and clover) occurred showed that increased streamflow was due to two mechanisms: greater flow of water through the root zones to recharge the water table and increased content of water in aquifers that induced drainage of groundwater directly to the stream (Ruprecht and Schofield, 1989). Finally, conversion of deep-rooted shrubs to shallow-rooted annual grasses produced large increases (59 percent as a proportion of precipitation) in groundwater discharge that can be measured in the form of baseflow (Pitt et al., 1978).

A conversion from relatively deep-rooted perennial shrubs to shallow-rooted annual brome grasses would increase net infiltration by reducing the amount of water transpired over a growing season. A pulse of infiltrating water becomes net infiltration when it moves below the rooting zone. Under the current climate, net infiltration typically occurs from winter storms because of the low evapotranspiration demand in the winter that allows wetting pulses more time to reach depths below the rooting zone. By the end of a growing season, it is typical for the entire thickness of the rooting zone to be dry, as arid-zone plants extract all useable moisture. As the brome rooting zone is much thinner than the shrub rooting zone, there is less distance for wetting pulses to travel to escape evapotranspiration, and a greater proportion of the wetting pulses becomes net infiltration. If no shrubs are present, moisture would remain in the soil below the evaporation zone and potentially percolate downward during and after the next precipitation event. Cline et al. (1977) compared annual water use in an annual grass community with that in a shrub/grass community. It was concluded that twice as much water was extracted by the perennial community compared to the annual grass community.

Interestingly, a brome-dominated landscape may actually transpire more than a comparable shrub-dominated landscape during the winter, when most net infiltration occurs, as shrubs tend to be dormant during the winter while brome grasses are slowly growing. The annual evapotranspiration rate for a brome-dominated landscape, however, is less than would occur for a shrub-dominated landscape because of a greater proportion of the infiltration from large precipitation events escaping the thin rooting depths of *Bromus* and the drop in transpiration during the off-growing season for the grasses. Brome grass is most effective at reducing infiltration during late winter and spring, especially for the numerous, small precipitation events. For large precipitation events a greater portion of the precipitation in a *Bromus*-dominated area will become shallow infiltration, thus leading to increased percolation at depth.

Replacement of shrubs with brome grasses would directly affect infiltration on YM and indirectly affect regional groundwater levels. Replacement of shrubs with foxtail chess on YM, under current climatic conditions, may have a relatively minor effect on net infiltration because evaporative demand is high and soil water storage tends to be low in the thin soil mantle that predominates in the hillslope over the repository footprint. Changes would be more significant where soil thicknesses are larger, such as wash bottoms and the caprock environment. The effect can be bounded by contrasting estimates of mean annual infiltration (MAI) obtained under ambient conditions with and without shrubs. Numerous lines of evidence offered by the U.S. Department of Energy (DOE) suggest that deep percolation rates within the repository block are between 1 and 10 mm/yr (Bodvarsson et al., 1997), at least below the repository horizon, while Stothoff et al. (1996) produced a comparable estimate of roughly 20 mm/yr through simulations that completely neglected transpiration (yielding an upper-bound estimate for net infiltration in the presence of grasses in arid environments). Such comparisons are ultimately unsatisfying, because the comparisons are somewhat indirect. In addition, some of the data collected by the DOE may show early effects of brome replacement at YM. Ideally, it would be better to compare infiltration measured in the field with and without shrubs, but this is impractical for the rocky YM hillslopes. Instead, it is recommended that a direct comparison be performed through simulation to examine potential changes in net infiltration.

Even under current climatic conditions, widespread replacement of shrubs with brome grasses may begin to induce regionally significant recharge increases. Current estimates of recharge in the YM region vary from the high elevations in the north where recharge is 3 percent of the annual 200–300 mm precipitation to the low elevations in the south where recharge is less than 0.5 percent of the 100–200 mm precipitation based on water balance studies for the basins (CRWMS M&O, 1998). Due to the large evapotranspiration potential, especially at lower elevations, recharge predominately occurs as transmission losses in stream channels rather than interchannel recharge in the alluvial basins (Osterkamp et al., 1994). Long-term fluxes in alluvial basins to the north and east of YM within the NTS, are low, with perhaps an upper extreme of 2.6 mm/yr at one borehole (Conrad, 1993; Tyler, 1987; Tyler and Jacobsen, 1990). Simulations of bare-soil infiltration in deep alluvium (Stothoff, 1997) suggest that MAI could increase to more than 30 mm/yr under current climatic conditions in alluvial basins. However, even large increases in MAI would require significant periods of time to propagate the wetting pulses to deep water tables typical of many alluvial basins. Changes in recharge at higher elevations may also occur; although there is a question regarding the ability of cheatgrass to dominate in shallow soils typical of mountain slopes. Even if MAI instantaneously increased ten-fold, significant changes to the water table or groundwater fluxes at YM are unlikely to be seen for decades to centuries, due to the time lag required for net infiltration to reach the saturated zone. The response time, however, should be less than the aquifer residence time. Based on carbonate-aquifer residence times, Winograd et al. (1992) provide an upper bound on response time of less than 10,000 yr and perhaps on the order of several thousand years from waters discharged at Devil's Hole.

Two studies considered the effects of climate change on the Death Valley regional groundwater flow system, and these studies provide guidance for quantifying the effects of changing recharge. Czarnecki's (1985) simulations found that the water table below YM rose approximately 130 m when precipitation input was doubled. D'Agnese et al. (1997) simulations found that the water table rose from 60 to 150 m in the YM area for a climate producing five times as much recharge as under current conditions. Both studies used the Maxey-Eakin method (Maxey and Eakin, 1949) to apportion recharge (recharge increases with increasing elevation). Initial estimates, from the previous paragraph, of brome-induced recharge support the fact that a 30-fold increase would occur in the broad alluvial valleys. Replacing shrubs with brome grasses will probably produce a different pattern of recharge increase than does climate change, possibly resulting in a different flow system, but it is reasonable to assume that a similar magnitude of water table rise would occur if recharge increased by a similar factor (averaged over the flow system).

Under cooler and wetter conditions, the replacement of native shrub species with cheatgrass would induce conditions that have not occurred in the past. If past glacial climatic conditions were to recur in the future with cheatgrass as the dominant vegetative species, it is likely that recharge would be significantly greater than in the past, and the rise in the water table would also likely be greater than under past conditions. Predicting the magnitude of water table rise would require modeling at several levels, with perhaps the most important being the prediction of changes in net infiltration under changes in vegetation and climate for typical recharge locations. With these results, recharge patterns in the regional groundwater flow models could be adapted to represent the altered vegetative conditions. A detailed autecological understanding of controlling factors for cheatgrass must be developed to provide realistic input to such a regional simulation.

4.2 INDIRECT INFLUENCES ON YUCCA MOUNTAIN HYDROLOGY

Replacement of shrubs by brome grasses may indirectly affect infiltration rates by affecting the surficial materials over shallow bedrock. The simulations reported by Stothoff (1997) are strongly affected by the depth and texture of the surficial cover materials, with MAI decreasing as soil thickness increases and soil texture becomes finer. Replacement of shrubs by brome grasses at YM will likely lead to enhanced erosion rates of surficial materials with decreasing soil thicknesses and concomitant loss of finer grain sizes on ridges and hillslopes. Observations on hillslope locations in California where brome grasses have replaced shrubs, with replacement enhanced because of anthropogenic activities, indicate that erosion is greatly enhanced in these areas, primarily because of slumping. The relatively shallow-rooted brome grasses may offer less resistance to mass wasting on hillslopes than the more deeply rooted shrubs by providing less resistance to slumping or creep, although soils present on YM are already so shallow that creep is likely not a dominant process.

Dense covers of grasses offer greater splash protection and overland-flow resistance—to more efficiently trap fine particles—than offered by the more sparse ground-covering shrubs. Such protection is no longer present when a fire has removed the grass cover. Thus, the expected higher fire frequency for grasslands compared to present shrub cover may result in a net soil loss due to enhanced erosion during those relatively rare rainfall events that occur with no vegetative protection for the soil.

Changes to soil profiles due to brome invasion might be more significant as the climate becomes cooler and wetter. Based on field observations at YM and a future climate analog site at Phinney Canyon (an east-draining canyon at roughly 6,500–7,500 ft in the nearby Grapevine Mountains), it is likely that soils were considerably finer and deeper at YM during portions of previous glacial cycles than exist at present.

Soil development has many feedback mechanisms, including those provided by vegetation. Disruption of previous vegetation replacement cycles may prevent recurrence of past developmental processes resulting in a significantly shallower and coarser soil cover than would otherwise have occurred. If the protection from erosion offered by grasses enhances soil development, the deeper and finer soils would enhance evaporation, partially offsetting the reduced transpiration that brome grasses offer compared to shrubs. If soil development is disrupted, evaporation as well as transpiration may be reduced relative to previous glacial cycles, which may increase MAI to unprecedented levels.

5 SUMMARY

Two naturalized Eurasian weedy brome grasses, foxtail chess (*B. madritensis* ssp. *rubens* L.) and cheatgrass (*B. tectorum* L.), have been present in the YM area since at least the 1930's. These species are documented as replacing native shrubs across much of western North America. Currently, brome grasses are actively replacing shrubs across southern Nevada. There is a heavy presence of foxtail chess and a lighter presence of cheatgrass at YM, with drought-prone areas such as low-elevation south-facing slopes appearing to undergo more active replacement. In the vicinity of nearby Shoshone Mountain, fire-burned areas 4–40 yr old also show heavy infestations of foxtail chess and cheatgrass.

Weedy annual brome grasses and well-established native shrubs can easily coexist, as they inhabit different ecological niches, shallow-rooted winter annuals versus deep-rooted perennials. However, such coexistence may be transitory because of several effective mechanisms for replacement of shrubs with brome grasses. This includes greatly enhanced fire rates (that are much more frequent than the natural shrub life expectancy), increased mobility of parasitic vegetation, and probably the most important mechanism, greatly reduced survival rates for vulnerable shrub seedlings. Without recruitment of seedlings to replace shrubs dying of old age and other factors, replacement will occur over the normal shrub lifetime, perhaps 30–100 yr.

Deep soils are ideal substrate for brome grasses, and it is likely that foxtail chess will replace the native shrub species at lower elevations and cheatgrass at higher elevations. Under cooler and wetter climate conditions, cheatgrass would be expected to dominate over foxtail chess. It has not been established whether brome grasses are likely to replace native shrubs and trees (i) on shallow rocky slopes, such as exist at YM; (ii) under monsoonal conditions; and (iii) during much cooler and wetter climatic conditions. Photographs shown in this report demonstrate, however, that under current climatic conditions, replacement by foxtail chess is occurring on YM slopes. Cheatgrass can grow and dominate, at least in disturbed areas, up to elevations 7,500–8,000 ft that provide cooler and wetter conditions than full glacial maximum conditions at YM.

Replacement of native shrubs with brome grasses would be expected to increase significantly the net infiltration and recharge to the regional aquifer, even under current climatic conditions, raising the water table and increasing groundwater fluxes. It is unlikely, however, that significant changes in regional hydrology would be noticed within less than a century. If replacement of shrubs with brome grasses occurs over large areas of the Death Valley regional groundwater flow system under cooler and wetter portions of future glacial cycles, unprecedented amounts of recharge may occur, possibly raising the water table beneath YM to unprecedented elevations. Under full glacial maximum conditions, the upper elevation for brome dominance would be much lower than at present, so replacement is most likely in alluvial valleys. Also, if the brome grasses are successful in removing shrubs over the repository footprint, unprecedented magnitudes of net infiltration fluxes may occur so that similar unprecedented fluxes of deep percolation may pass through the repository footprint.

Current work to evaluate the potential impact of brome grass invasion is focused on establishing bounded estimates of its effect on infiltration on YM over the repository and the effect of increased recharge in deep alluvial valleys on the flow pathways and water table elevation. A bounding calculation of the effect of increased infiltration caused by *Bromus* over the repository can be modeled using existing data and models. The bounding analysis of increased recharge over the alluvial valleys of the regional saturated zone groundwater model requires further refinement of potentially affected areas. Note that all areas (alluvial basins and mountain ranges) could be affected. It is believed, however, that recharge over the alluvial basins will have the largest effect on flow paths and water table rise. Studies are underway in the regional groundwater catchment using satellite data and local ground confirmation to delineate current and past areas of brome grass invasion.

Based on the results of the bounded analyses, further work would involve characterization of brome grass invasion processes: (i) determination of rooting depths and soil-moisture uptake patterns under various soil conditions for both cheatgrass and foxtail chess; (ii) determination of elevational extent of *Bromus* under current climatic conditions for use as a predictor for future climatic conditions including cooler and wetter future climates and the potential for *Bromus* invasion under monsoonal conditions; and (iii) determination of the relationship of *Bromus* invasion with soils, aspect, and slope. As information is developed from the characterization of brome grass invasion extent and processes, the models for infiltration and recharge would be modified. Estimates of infiltration from 1D models would be used to estimate the impact in different environments (e.g., ridgetops, upland slopes, and alluvial valleys). As the Nuclear Regulatory Commission regional saturated groundwater flow model is developed, the changes in infiltration rates would be used as input for the recharge boundary condition to constrain possible rises in the water table because of brome grass invasion.

6 REFERENCES

Beatley, J.C. 1966. Ecological status of introduced brome grasses (*Bromus* spp.) in desert vegetation of southern Nevada. *Ecology* 47: 548–554.

Beckstead, J., S.E. Meyer, and P.S. Allen. 1996. *Bromus tectorum* seed germination: Between-population and between-year variation. *Canadian Journal of Botany* 74: 875–882.

Billings, W.D. 1994. *Ecological Impacts of Cheatgrass and Resultant Fire on Ecosystems in the Western Great Basin.* USFS General Technical Report INT–GTR–313: 22–30. Ogden, UT: U.S. Forest Service.

Blank, R.R., F. Allen, and J.A. Young. 1994. Growth and elemental content of several sagebrush steppe species in unburned and post-wildfire soil and plant effects on soil attributes. *Plant and Soil* 164: 35–41.

Bodvarsson, G.S., T.M. Bandurraga, and Y.S. Wu, eds. 1997. *The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment.* LBNL–40376. Berkeley, CA: Lawrence Berkeley National Laboratory.

Bosch, J.M., and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3–23.

Brown, D.E., and R.A. Minnich. 1986. Fire and changes in creosote bush scrub of the Western Sonoran Desert, California. *American Midland Naturalist* 116: 411–422.

Bull, W.B. 1991. *Geomorphic Responses to Climatic Change*. Oxford, England: Oxford University Press.

Civilian Radioactive Waste Management System, Management & Operating Contractor. 1998. Yucca Mountain Site Description, Book 2–Section 4,5. B00000000–01717–5700–00019, Revision 00 September 1998. Las Vegas, NV: TRW Environmental Safety Systems, Inc.

Cline, J.F., D.W. Uresk, and W.H. Rickard. 1977. Comparison of soil water used by a sagebrush-bunchgrass and a cheatgrass community. *Journal of Range Management* 30: 199–201.

Clokey, I.W. 1951. *Flora of the Charleston Mountains, Clark County, Nevada.* Berkeley, CA: University of California Press.

Conrad, S.H. 1993. Using environmental tracers to estimate recharge through an arid basin. *Proceedings of the Fourth Annual International Conference on High-Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society: 132–137.

Corbineau, F., D. Belaid, and D. Come. 1992. Dormancy of *Bromus rubens* L. seed in relation to temperature, light, and oxygen effects. *Weed Research* 32: 303–310.

Czarnecki, J.B. 1985. *Simulated Effects of Increased Recharge on the Ground-Water Flow System of Yucca Mountain and Vicinity, Nevada–California.* USGS Water-Resources Investigations Report 84-4344. Denver, CO: U.S. Geological Survey.

D'Agnese, F.A., G.M. O'Brien, C.C. Faunt, and C.A. San Juan. 1997. *Simulated Effects of Climate Change on the Death Valley Regional Ground-Water Flow System, Nevada and California.* USGS Water-Resources Investigations Report (draft). Denver, CO: U.S. Geological Survey.

Emmerich, F.L., F.H. Tipton, and J.A. Young. 1993. Cheatgrass: changing perspectives and management strategies. *Rangelands* 15: 37–40.

Evans, R.A., and J.A. Young. 1982. Microhabitat variation in relation to weed seed germination and seedling emergence. *Biometeorology in Integrated Pest Management.* J.L. Hatfield and I.J. Thomason, eds. New York: Academic Press, Inc.: 421–448.

Fayer, M.J., and T.L. Jones. 1990. *UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Model.* PNL–6779. Richland, WA: Pacific Northwest Laboratory.

Harper, K.T., R.Van Buren, and S.G. Kitchen. 1996. *Invasion of Alien Annuals and Ecological Consequences in Salt Desert Shrublands of Western Utah.* USFS General Technical Report INT–GTR–338: 58–65. Ogden, UT: U.S. Forest Service.

Harris, G.A. 1967. Some competitive relationships between *Agropyron spicatum* and *Bromus tectorum. Ecological Monographs* 37: 89–111.

Hickman, J.C., ed. 1993. *The Jepson Manual: Higher Plants of California.* Berkeley, CA: University of California Press.

Hinds, W.T. 1975. Energy and carbon balances in cheatgrass: An essay in Autecology. *Ecological Monographs* 45: 367–388.

Hulbert, L.C. 1955. Ecological studies of *Bromus tectorum* and other annual bromegrasses. *Ecological Monographs* 25: 181–213.

Hull, A.C., Jr. 1963. Competition and water requirements of cheatgrass and wheatgrasses in the greenhouse. *Journal of Range Management* 27: 366–368

Hunter, R. 1991. *Bromus* invasions on the Nevada Test Site: Present status of *B. rubens* and *B. tectorum* with notes on their relationship to disturbance and altitude. *Great Basin Naturalist* 51: 176–182.

Klemmedson, J.O., and J.G. Smith. 1964. Cheatgrass (*Bromus tectorum* L.). *Botanical Review* 30: 226–262.

Mack, R.N. 1981. Invasion of *Bromus tectorum* L. into western North America: An ecological chronical. *Agro-Ecosystems* 7: 145–165.

Maxey, G.B., and T.E. Eakin. 1949. *Ground Water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada.* Bulletin 8. Carson City, NV: Department of Conservation and Natural Resources, State of Nevada.

McMurray, M.H., S.H. Jenkins, and W.S. Longland. 1997. Effects of seed density on germination and establishment of a native and an introduced grass species dispersed by granivorous rodents. *American Midlands Naturalist* 138: 322–330.

Melgoza, G., R.S. Nowak, and R.J. Tausch. 1990. Soil water exploitation after fire: Competition between *Bromus tectorum* (cheatgrass) and two native species. *Oecologia* 83: 7–13.

Meyer, S.E., P.S. Allen, and J. Beckstead. 1997. Seed germination regulation in *Bromus tectorum* (Poaceae) and its ecological significance. *Oikos* 78: 475–485.

Osterkamp, W.R., L.J. Lane, and C.S. Savard. 1994. Recharge estimates using a geomorphic/distributed-parameter simulation approach, Amargosa River Basin. *Water Resources Bulletin* 30(3): 493-507.

Peck, A.J., and D.R. Williamson. 1987. Effects of forest clearing on groundwater. *Journal of Hydrology* 94: 47–65.

Pitt, M.D., R.H.Burgy, and H.F. Heady. 1978. Influences of brush conversion and weather patterns on runoff from a northern California watershed. *Journal of Range Management* 31: 23–27.

Rasmuson, K.E., J.L. Boone, and S.L. Petersen. 1999. *Final Report: Plant and Soil Related Processes Along a Natural Thermal Gradient at Yucca Mountain, Nevada.* Civilian Radioactive Waste Management System B00000000–01717–5705–00109. Revision 00. Las Vegas, NV: TRW Environmental Safety Systems, Inc.

Richardson, J.M., D.R. Geary, and L.A. Morrow. 1989. Influence of moisture deficits on the reproductive ability of downy brome (*Bromus tectorum*). *Weed Science* 37: 525–530.

Rickard, W.H. 1985. Shoot production and mineral nutrient assimilation in cheatgrass communities. *Northwest Science* 59: 169–179.

Ruprecht, J.K., and N.J. Schofield. 1989. Analysis of streamflow generation following deforestation in southwest Western Australia. *Journal of Hydrology* 105: 1–17.

Ruprecht, J.K., and N.J. Schofield. 1991a. Effects of partial deforestation on hydrology and salinity in high salt storage landscapes: I. Extensive block clearing. *Journal of Hydrology* 129: 19–38.

Ruprecht, J.K., and N.J. Schofield. 1991b. Effects of partial deforestation on hydrology and salinity in high salt storage landscapes: II. Strip, soils and parkland clearing. *Journal of Hydrology* 129: 39–55.

Russell, C.E., J.W. Hess, and S.W. Tyler. 1987. Hydrogeologic investigations of flow in fractured tuffs, Ranier Mesa, Nevada Test Site. Flow and Transport Through Unsaturated Fractured Rock.

D.D. Evans and T.J. Nicholson, eds. *Geophysical Monograph 42*. Washington, DC: American Geophysical Union.

Schmidt, M.R. 1989. Classification of upland soils by geomorphic and physical properties affecting infiltration at Yucca Mountain, Nevada. Master's thesis, Colorado State University.

Schultz, B.W., and W.K. Ostler. 1995. *Effects of Prolonged Drought on Vegetation Associations in the Northern Mojave Desert.* USFS General Technical Report INT–GTR–315: 228–235. Ogden, UT: U.S. Forest Service.

Sparks, S.R., N.E. West, and E.B. Allen. 1990. *Changes in Vegetation and Land Use at Two Townships in Skull Valley, Western Utah.* USFS General Technical Report INT–GTR–276: 26–36. Ogden, UT: U.S. Forest Service.

Spaulding, W.G. 1994. *Paleohydrologic Investigations in the Vicintiy of Yucca Mountain: Late Quaternary Paleobotanical and Paleonological Records.* Nuclear Waste Project Report NWPO–TR–022–94. Las Vegas, NV: State of Nevada Agency for Nuclear Projects.

Spaulding, W.G., and L.J. Graumlich. 1986. The last pluvial climatic episodes in the deserts of southwestern North America. *Nature* 320: 441–444.

Stewart, G., and A.C. Hull. 1949. Cheatgrass (*Bromus tectorum* L.)—An ecological intruder in southern Idaho. *Ecology* 30: 58–74.

Stothoff, S.A. 1997. Sensitivity of long-term bare soil infiltration simulations to hydraulic properties in an arid environment. *Water Resources Research* 33(4): 547–558.

Stothoff, S.A., H.M. Castellaw, and A.C. Bagtzoglou. 1996. Simulating the Spatial Distribution of Infiltration at Yucca Mountain, Nevada. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Tausch, R.J., R. Svecar, and J.W. Burk. 1994. *Patterns of Annual Grass Dominance on Anaho Island: Implications for Great Basin Vegetation Management.* USFS General Technical Report INT–GTR–313: 120–125. Ogden, UT: U.S. Forest Service.

Tausch, R.J., J.C. Chambers, R.R. Blank, and R.S. Nowak. 1995. *Differential Establishment of Perennial Grass and Cheatgrass Following Fire on an Ungrazed Sagebrush-Juniper Site.* USFS General Technical Report INT–GTR–315: 252–257. Ogden, UT: U.S. Forest Service.

Thill, D.C., K.G. Beck, and R.H. Callihan. 1984. The biology of downy brome (*Bromus tectorum*). *Weed Science* 32: 7–12.

Trammel, M.A., and J.L. Butler. 1995. Effects of exotic plants on native ungulate use of habitat. *Journal of Wildlife Management* 59: 808–816.

Tyler, S.W. 1987. *Review of Soil Moisture Flux Studies at the Nevada Test Site, Nye County, Nevada.* Publication 45058. Reno, NV: Desert Research Institute.

Tyler, S.W., and R.L. Jacobson. 1990. Soil moisture flux studies on the nevada test site: a review of results and techniques. *Hydraulics/Hydrology of Arid Lands, Proceedings of the International Symposium.* New York: American Society of Civil Engineers, HYIR Division: 718–724.

Updike, D.R., E.R. Loft, and F.A. Hall. 1990. *Wildfires on Big Sagebrush/Antelope Bitterbrush Range in Northeastern California: Implications for Deer Populations.* USFS General Technical Report INT–GTR–276: 41–46. Ogden, UT: U.S. Forest Service.

Young, J.A., and R.A. Evans. 1975. Germinability of seed reserves in a big sagebrush community. *Weed Science* 23: 358–364.

Young, J.A., and R.A. Evans. 1976. Response of weed populations to human manipulations of natural environment. *Weed Science* 24: 186–190.

Young, J.A., and R.A. Evans. 1978. Population dynamics after wildfires in sagebrush grasslands. *Journal of Range Management* 31: 283–289.

Young, J.A., and R.A. Evans. 1985. Demography of *Bromus tectorum* in *Artemisia* communities. *Handbook of Vegetation Science. Part III: The Population Structure of Vegetation.* J. White, ed. Boston, MA: Dr. W. Junk Publishers: 490-502.

Young, J.A., and F. Tipton. 1990. *Invasion of Cheatgrass into Arid Environments of the Lahontan Basin.* USFS General Technical Report INT–GTR–276: 37–40. Ogden, UT: U.S. Forest Service.

Young, J.A., R.A. Evans, and R.E. Eckert, Jr. 1969. Population dynamics of downy brome. *Weed Science* 17: 20–26.

Young, J.A., R.A. Evans, and B.L. Kay. 1987. Cheatgrass. *Rangelands* 9: 266–270.

Whisenant, S.G. 1990. *Changing Fire Frequencies on Idaho's Snake River Plains: Ecological and Management Implications.* USFS General Technical Report INT–GTR–276: 4–10.

Winograd, I.J., T.B. Copen, J.M. Landwehr, A.C. Riggs, K.R. Ludwig, B.J. Szabo, P.T. Kolesar, and K.M. Rivesz. 1992. Continuous 500,000-Year Climate Record from Vein Calcite in Devils Hole, Nevada. *Science* 258: 255-260.