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The Protective Cap/Biobarrier Experiment: A Study of Alternative Evapotranspiration Caps for the Idaho National Engineering and Environmental Laboratory

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A study of Alternative Evapotranspiration Caps
for the Idaho National Engineering and Environmental Laboratory

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The exclusion of ecological principles is, in my opinion, the greatest failing of current practices in designing capping technology.

T. E. Hakonson (1994)

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EXECUTIVE SUMMARY

Shallow land burial has been the most common method for disposing of industrial, municipal, and low-level radioactive waste. However, conventional landfill practices are often inadequate to preclude movement of hazardous materials to ground water or biota. Hydrologic processes account for most waste repository problems. Percolation of water into the waste zone may leach and transport toxic materials into groundwater. Water in the waste zone may also encourage growth of plant roots and transport of toxic materials to aboveground foliage.

Most final covers on hazardous waste landfills in the United States must meet performance standards specified under subtitle C of the Resource Conservation and Recovery Act (RCRA). The US Environmental Protection Agency's (EPA) recommended cover for arid and semiarid climates includes a compacted clay layer overlain by an impervious flexible membrane liner (FML), which, in turn, is overlain by vegetated topsoil. Such covers have been widely used, but they often fail in dry climates because the compacted clay layer dries and cracks. RCRA regulations allow EPA to consider alternative cap designs demonstrated to meet equivalency criteria.

In humid regions, keeping water received as precipitation from reaching interred wastes can be a formidable problem, but, in arid or semiarid areas, a natural ecosystem analogue provides a simple and elegant solution. Because the potential to evaporate water far exceeds the amount of water received as precipitation, many aridland ecosystems return all of the water received to the atmosphere via evapotranspiration (ET). The soil serves as a reservoir, temporarily storing precipitation that is not immediately evaporated. In turn, plants extract that water from the soil and return it to the atmosphere. Hence, soil and plants are the principal components of an ET cap. The soil must be sufficiently deep to store water received, and a healthy stand of perennial plants must be present to empty that storage reservoir during each growing season.

This report presents results from the final phase of nearly two decades of research on ET caps at the Idaho National Engineering and Environmental Laboratory (INEEL). The first phase of this research demonstrated that a soil cap 2 m in depth supporting a healthy stand of perennial plants should preclude water from reaching buried wastes at the INEEL. However, several issues related to the performance of ET caps were not addressed in the first study, including: 1) the impacts of placing biological intrusion barriers in an ET cap, 2) the potential effects of climate change on cap performance, and 3) the performance of a diverse community of native plants compared to that of monocultures. To address these issues, the Protective Cap/Biobarrier Experiment (PCBE) was initiated in 1993. The ultimate goal was to confidently recommend an effective, economical ET cap for the INEEL and climatically similar repositories, a cap constructed of natural materials that will function with minimal maintenance over the long term as a natural ecosystem. Specific objectives of the PCBE were to:

1) compare the performance of caps having biobarriers with that of soil-only caps and that of caps based on EPA recommendations for RCRA caps,

2) examine the effects of intrusion barriers placed at different depths on water percolation, water storage capacity, plant rooting depths, and water extraction patterns.
3) evaluate the performance of caps receiving higher precipitation than expected under either the present climate or that anticipated in the foreseeable future.
4) compare the performance of a community of native species on ET caps to that of caps vegetated with a monoculture of crested wheatgrass.

The PCBE was a field-scale experiment, consisting of three replicates of four cap configurations, two vegetation types, and three irrigation treatments. The four cap configurations were:
1) soil-only caps consisting of 2.0 m of homogeneous soil.
2) shallow biobarrier caps that included a biobarrier consisting of 0.3 m of river cobble sandwiched between 0.1 m layers of crushed gravel. This biobarrier was placed at a depth of 0.5 m within a 2-m soil profile.
3) deep biobarrier caps having a 0.5-m biobarrier at a depth of 1 m within a 2 m soil profile. The biobarrier was identical to that of shallow biobarrier caps.
4) RCRA caps having 1 m of soil overlying a flexible membrane liner and 0.6 m of compacted clay.

Precipitation regimes were ambient precipitation, 200 mm of supplemental irrigation applied at four biweekly intervals during summer, and 200 mm of supplemental irrigation applied rapidly in late fall or early spring. The two vegetation types were a mix of twelve native species and a monoculture of crested wheatgrass. The period of study (1994-2000) included near extremes of both low and high annual precipitation for the 50 years of record at the INEEL.

Under ambient precipitation and summer irrigation treatments, all cap types performed satisfactorily and similarly. Given the present and predicted climate for the upper Snake River Plain, a landfill cap constructed according to any of the cap configurations in this study should prevent water received as precipitation from reaching interred wastes. The results indicate that even a large increase in summer precipitation would not adversely impact cap performance. With increased winter precipitation (fall/spring irrigation treatment), differences in cap performance became more important, but the soil-only and biobarrier caps were still capable of storing and returning to the atmosphere far more moisture than the precipitation expected under current climate change scenarios. Thus, the soil-only and biobarrier caps should preclude water from reaching buried wastes, even with a considerable increase in winter precipitation.

Despite generally satisfactory performance, there were important differences that translate to advantages or disadvantages of the various cap configurations. The 1 m of soil in the RCRA cap was inadequate to store the ambient precipitation received during 1995, an exceptionally wet year. Furthermore, under fall/spring irrigation RCRA caps often had little reserve storage capacity at the beginning of a growing season, and drainage off the FML was sometimes observed. Therefore, provision would have to be made for disposing of water that would occasionally drain off the cap over the FML. This would increase construction complexity and cost of the RCRA cap.

Roots of numerous species were able to bridge the 0.5-m thick biobarrier and extract water from the underlying soil, so indeed it is possible to have a portion of the storage reservoir below a biobarrier. However, 0.5 m of soil above a biobarrier was insufficient to store the precipitation received in most years, so water routinely percolated into the soil below, providing a reservoir of deep soil moisture. Placement of the biobarrier at a shallow depth caused strong selection for gray rabbitbrush, a native shrub known to rely primarily on deep moisture reserves. Encouraging the growth of this deeply rooting species could result in intrusion of roots into buried wastes if any water was available in the waste zone. Another disadvantage of the shallow-biobarrier configuration is that it may not provide sufficient depth of soil to accommodate the needs of burrowing mammals and insects, which might encourage such species to burrow into and possible through a biobarrier.

Under ambient precipitation and summer irrigation, there was seldom any change in water content below deep biobarriers, and 1 m of soil above the biobarriers was often sufficient to store ambient precipitation plus fall/spring irrigation. The capillary break between fine textured soil and the gravel at the top of the biobarrier maximizes the amount of water stored in the overlying soil. Plants did extract water from soil below deep biobarriers, but only when water content of the soil immediately below the barrier was at least 25% by volume. This suggests a threshold water content below which plants are unable to detect the presence of water below a 0.5-m thick biobarrier.

This study confirmed that a cap consisting of 2 m of soil would prevent percolation of water into interred wastes so long as healthy perennial vegetation is present to empty that storage reservoir each year. The results indicate that, under present climatic conditions or those predicted for the future, the soil wetting front would seldom reach the bottom of a 2-m soil cap. Once plants extract water from the entire soil profile, the expected hydraulic conductivity of the dry soil near the bottom of the cap would be very low, about 10^{-12} to 10^{-10} cm/s. Because root activity would be limited to those depths having plant-available water, we would not expect roots to grow beyond the depth of the wetting front each year. Thus, root intrusion into buried wastes should not be a problem once the vegetation initially dries the soil cap.

Using a combination of transplanting and seeding, we readily established diverse communities on the experimental plots. Shrubs, perennial grasses, and perennial forbs all grew vigorously. This study repeatedly demonstrated that a mixture of perennial species would use all of the plant available water in a 2-m storage reservoir, even when the soil in that reservoir was completely saturated early in the growing season. The monocultures of crested wheatgrass also established quickly and grew vigorously. However, after supplemental irrigation to facilitate establishment and a very wet growing season in 1995, the stands of crested wheatgrass were so dense that they became self inhibiting. Live cover on those plots subsequently decreased by about 50%. On crested-wheatgrass caps receiving supplemental irrigation, not all of the plant available water was withdrawn each year. Higher end-of-season water content on crested-wheatgrass caps was likely attributable to both lower cover and the absence of shrubs. Shrubs such as sagebrush and the rabbitbrushes remain active late in the growing season, continuing to extract soil moisture after many grasses and forbs are senescent.

Given these results, we recommend two cap configurations: a soil-only cap consisting of a 2-m depth of homogeneous soil or a cap consisting of a 1.2-m depth of homogeneous soil overlying a 0.5-m thick gravel/cobble intrusion barrier. Caps constructed according to either of these configurations should preclude virtually any precipitation water from reaching interred wastes. A major advantage of a soil-only cap is simplicity of construction, but a relatively large amount of soil is required. Construction cost will depend largely on availability of soil and the distance it must be transported. If fill soil is limited and if gravel and cobble are readily available, then a cap incorporating a biobarrier and requiring less soil may be less expensive.

We recommend that, if a biobarrier is used, it should be placed at the bottom of the soil reservoir. Although 1 m of soil above a biobarrier was generally adequate to store precipitation received, water did percolated below the biobarrier on two of 18 deep-biobarrier subplots during 1995, the wettest year on record at the INEEL. Therefore, we recommend a minimum of 1.2 m of soil overlying a biobarrier. A cap consisting of 1.2 m of soil overlying the capillary break of the biobarrier should be more than adequate to store precipitation received during exceptionally wet years. Furthermore, this configuration should prevent intrusion by burrowing animals, and it should restrict root growth so long as the underlying materials are relatively dry.

For new burial sites, we recommend constructing a level cap on grade with surrounding terrain. This eliminates the necessity of accommodating drainage off cap layers, eliminates side slope problems, and reduces the potential for wind or water erosion. For ET caps constructed to cover existing landfills or contaminated soil, it may be necessary to construct the entire cap above grade. In such a case, it may be desirable to configure the cap with a slight slope on the surface (e.g., 2%) to help prevent pooling of water on the surface following snowmelt or heavy precipitation. For any cap constructed over an existing landfill or contaminated soil, we recommend placing a biobarrier on top of the existing cover or soil. This will help ensure that no moisture moves into the contaminated materials. The new cap should be constructed late in the growing season when the soil of the existing landfill or contaminated area is dry. This will reduce the likelihood of roots growing from the new cap into the contaminated zone.

For a cap to function effectively and consistently, a healthy stand of perennial, drought-adapted plants is essential. The objective is to establish a plant community that will be self-maintaining. An analogue to a natural sagebrush-perennial grass community performed better than a perennial grass monoculture. Therefore, we recommend establishing a diverse community of perennial species consisting of shrubs, perennial grasses, and perennial forbs on ET caps at the INEEL. Specific recommendations for plant materials and planting techniques are discussed.

We conclude that an ET cap constructed according to the recommendations above will preclude precipitation water from reaching interred wastes at the INEEL and climatically similar sites. The recommended cap configurations provide a low cost, low maintenance alternative to EPA's recommended RCRA cap and to more complex, highly engineered designs.

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1.0 INTRODUCTION

Shallow land burial has been the most common method for disposing of industrial, municipal, and low-level radioactive waste. However, in recent decades it has become apparent that conventional landfill practices are often inadequate to preclude movement of hazardous materials to ground water or biota (Jacobs et al. 1980, Hakonson et al. 1982, Suter et al. 1993, Daniel and Gross 1995, Bowerman and Redente 1998). Hakonson (1994) reported that over 3000 landfills containing radioactive or other hazardous wastes had been created and decommissioned at Department of Energy (DOE) facilities over the course of the United State's nuclear weapons and energy research programs. Current federal and state regulations will require remediation of most of these sites, but relatively few sites will require physical removal of the source material or in-situ treatment to convert that material to a less toxic state (Hakonson 1994). Consequently, Hakonson (1994) emphasized that "capping technologies will be heavily used" to contain radioactive and other hazardous wastes in landfills.

Most final covers on hazardous waste landfills in the United States are required to meet performance standards specified under subtitle C of the Resource Conservation and Recovery Act (RCRA; 40 CFR §264). Containment is the primary objective of these standards. Containment involves keeping contaminants in place and preventing generation of leachate that might cause the contaminants to migrate (Hakonson 1994).

Research has shown clearly that hydrologic processes account for most waste repository problems (Fisher 1986, Nyhan et al. 1990, Nativ 1991). If wastes are not properly isolated, water received as precipitation can move through the landfill cover and into the wastes (Healy 1989). The presence of water may cause plant roots to grow into the waste zone and transport of toxic materials to aboveground foliage (Hakonson and Bostick 1976, Klepper et al. 1979, Arthur 1982, Hakonson et al. 1992, Bowerman and Redente 1998). Likewise, percolation of water through the waste zone may transport contaminants into groundwater (Fisher 1986, Bengtsson et al. 1994). Some landfill designs specify emplacement of an impervious liner beneath the wastes to prevent contaminants from moving into groundwater. In such cases, water moving through the wastes can pool on the liner and leach toxic or radioactive compounds from the wastes. Subsequent failure or overflowing of the liner may transport leachate into groundwater. Avoidance of such "bathtub" conditions is a major concern in designing radioactive waste landfills (10 CFR §61.51).

The US Environmental Protection Agency's recommended cover for arid and semiarid climates includes a compacted clay layer overlain by a impervious flexible membrane liner (FML), which, in turn, is overlain by vegetated topsoil (USEPA 1989). Such "traditional covers" have been widely used, but experience has shown that they often fail in dry climates because the compacted clay layer dries and cracks (Suter et al. 1993, Daniel and Gross 1995). Dwyer (1998) cited a study of 544 California landfills in which 72% to 86% of landfills with clay barrier layers were failing. The EPA guidelines acknowledge that their recommended design may not be very effective in arid regions and that such covers are expensive and difficult to construct. The RCRA regulations allow EPA to consider alternative designs demonstrated to meet equivalency criteria.

In humid regions, keeping water received as precipitation from reaching interred wastes can be a formidable problem, but in arid or semiarid areas, it may be possible to apply a simple and elegant "ecological engineering" solution (Anderson 1997). Under arid climates, the potential to evaporate water far exceeds the amount of water received from precipitation. Thus, to preclude water from percolating into buried wastes, water received as precipitation must be stored on site until it can be evaporated. This is precisely how natural aridland ecosystems function. The soil serves as a reservoir, temporarily storing precipitation that is not immediately evaporated. In turn, plants extract that water from the soil and return it to the atmosphere. Hence, soil and plants are the principal components of what has become known as an "evapotranspiration cap" (ET cap, also know as "alternative earthen final cover" [Benson et al. 2001]). The soil cap must be sufficiently deep to store water received while plants are dormant or from heavy precipitation events. The other crucial component is a healthy stand of perennial plants that are capable of emptying that storage reservoir during each growing season.

The literature concerning landfill closures often mentions the role of plants in stabilizing a site to control erosion, but the more important role that plants play in removing water from throughout a soil profile has received less attention (e.g., Nativ 1991, Suter et al. 1993). Direct evaporation removes water from relatively shallow depths of soil, whereas plants typically extract water from the entire soil profile. Earlier research at the INEEL showed that soils without vegetation lose relatively little water over a growing season (Anderson et al. 1993). If plants are not present, most of the soil will reach field capacity within a year or so and then remain at that level (ibid.). Consequently, any significant precipitation event likely will cause drainage. Porro (2001) reported similar results from unvegetated test caps at the INEEL that were irrigated until drainage occurred. Following cessation of drainage, water content on all caps remained high, and melting snow resulted in drainage in subsequent years (ibid.). Researchers at the Hanford Site in eastern Washington found that drainage would eventually occur from unvegetated soil caps under very low annual precipitation (160 mm annually; Sackschewsky et al. 1995). Indeed, plants are essential on an ET cap to empty the soil's storage reservoir each year.

Over a growing season in an arid or semiarid climate, plants can use enormous amounts of water if it is plentiful. For example, alfalfa growing in southern Idaho can extract 12 mm of water from the soil in a single hot summer day. Average water use of an irrigated alfalfa crop over a growing season is typically about 8 mm per day (Wright and Jensen 1972), equivalent to roughly four times the average annual precipitation of the area. A stand of Great Basin wildrye (Le*ymus cinereus*), a native bunchgrass, used over 530 mm of water during one growing season at the INEEL (Anderson et al. 1987). That is 2.4 times the mean annual precipitation for the area. As we further document in this report, the native vegetation of the INEEL has the potential to use far more water than would be expected to fall under the present or foreseeable climates, provided that the soil is sufficiently deep to store the precipitation received.

This report presents results from the final phase of nearly two decades of research addressing these concepts at the Idaho National Engineering and Environmental Laboratory (INEEL). The first phase of this research demonstrated conclusively that a soil cap 2 meters in depth supporting a healthy stand of perennial plants should be more than adequate to preclude water from reaching buried wastes at the INEEL (Anderson et al. 1987, 1991, 1993). Here we report results of the Protective Cap/Biobarrier Experiment (PCBE), a replicated field-scale experiment designed to compare the efficacy of four cap configurations and two vegetation types under three precipitation regimes. Based on the results of this project, we provide recommendations for the design and construction of evapotranspiration caps for final closure of landfills at the INEEL.

1.1 Rationale and Objectives for the PCBE

Although our first ET-cap project at the INEEL showed that a 2-m cap of soil could preclude precipitation water from reaching interred wastes, that project did not address several issues related to the performance of ET caps. Knowledge gaps include the impacts of placing biological intrusion barriers in an ET cap, the potential effects of climate change on cap performance, and the performance of a diverse community of native plants compared to that of monocultures (only monocultures were evaluated in the first ET-cap project; see Anderson et al. 1987, 1993). The rationale and PCBE objectives for each of these issues are detailed in the following sections. The ultimate goal of the PCBE was to confidently recommend an effective, economical ET cap for the INEEL and climatically similar repositories, a cap constructed of natural materials that will function with minimal maintenance over the long term as a natural ecosystem.

Effects of Biological Intrusion Barriers on Cap Performance. Concerns are often expressed that small mammals or other burrowing organisms might compromise the performance of such a cap. Indeed, researchers at the INEEL and elsewhere have demonstrated that burrowing by small mammals (Hakonson et al. 1982, Laundre 1993) and ants (Blom et al. 1994) can increase water infiltration and percolation by decreasing the bulk density of soil or creating channels for preferential flow. Burrowing animals also may transport contaminants to the surface (Arthur and Markham 1983, Arthur et al. 1986, 1987; see Suter et al. 1993 for a summary of animal intrusion effects). A biological intrusion barrier (biobarrier) consisting of a layer of rock placed within a protective soil cap will restrict the depth to which mammals can burrow (Hakonson et al. 1983, Hakonson 1986, Reynolds 1990). Tunneling by ants can be obstructed by sandwiching a layer of cobble between layers of gravel placed in the soil (Johnson and Blom 1997, Gaglio et al. 1998). Such an intrusion barrier placed within a soil cap should restrict animal burrowing, but the barrier may also constrain growth of plant roots. If roots were restricted to the soil above an intrusion barrier, the effective water storage reservoir of the soil cap would also be limited to the soil above the barrier. In this case, depth of emplacement of the intrusion barrier within a soil profile would be critical. On the other hand, if plant roots penetrated through the intrusion barrier and extracted water from the soil below it, depth of emplacement of the barrier might have little effect on the size of the water storage reservoir. Given these considerations, the first two objectives of the PCBE were:

Objective 1. To compare the hydrologic performance of caps having biobarriers with that of soil-only caps and that of caps based on EPA recommendations for RCRA caps.

Objective 2. To examine the effects of intrusion barriers placed at different depths on water percolation, water storage capacity, plant rooting depths, and water extraction patterns.

Effects of Climate Change on Cap Performance. Models of climatic change predict an increase in precipitation over the next 50 to 100 years for sagebrush steppe ecosystems, such as at the INEEL. Some models predict an increase in precipitation during summer, whereas others predict an increase during winter or early spring (Giorgi et al. 1994, Ferguson 1997). It is likely that a change in precipitation patterns, especially increased summer precipitation, would change the composition of vegetation and, in turn, could affect the performance of an ET cap. To investigate the implications of such climate changes, we included two supplemental irrigation treatments in addition to an ambient precipitation control in the PCBE; one irrigation treatment augments summer precipitation by 200 mm and the other augments winter/spring precipitation by the same amount. These supplemental treatments are approximately equal to the average precipitation received at the INEEL (220 mm); thus, they roughly doubled the average ambient precipitation. This amount is much more than that predicted by climate change models (Giorgi et al. 1994, Ferguson 1997). Our intent was to augment precipitation sufficiently to cause measurable vegetation and hydrologic responses to address the following objective:

Objective 3. To evaluate the performance of caps receiving higher precipitation than expected under either the present climate or that anticipated in the foreseeable future.

Comparison of Crested Wheatgrass Monocultures vs. Diverse Plant Communities as the Vegetation on ET Caps. Prior to the initiation of this project in 1993, most waste burial and other disturbed sites at the INEEL were planted with crested wheatgrass (*Agropoyron cristatum* or *A. desertorum*), species native to Europe and Asia. Because of their ease of establishment and tolerance of drought and livestock grazing, these species have been used widely for rangeland reclamation in the western United States and have become naturalized in many areas (Hull and Klomp 1966, Rogler and Lorenz 1983). At the INEEL, crested wheatgrasses tend to form persistent monocultures (Marlette and Anderson 1986), which makes them attractive candidates for vegetation on landfill caps. Anderson et al. (1987, 1993) found that crested wheatgrass grew well on simulated waste caps and would use all of the plant-available moisture in a 2.2-m soil cap, even during exceptionally wet years. Assuming that these species likely would be included in the plants established on ET caps at the INEEL, crested wheatgrass was planted in pure stands as one of the vegetation types.

Ecological theory predicts that a diverse plant community consisting of multiple life forms will be more stable and will more completely use resources such as soil moisture in comparison with a simple community (e.g., McNaughton 1977, 1993, Tilman et al. 1997b). Numerous recent studies support those predictions (e.g., Tilman and El Haddi 1992, Tilman and Downing 1994, Tilman et al. 1996, 1997a, Hector et al. 1999, Anderson and Inouye 2001). Analyses of long-term vegetation data from permanent plots at the INEEL indicate that areas having more species tend to maintain higher cover and fluctuate less in cover relative to the mean value, compared with areas supporting fewer species (Anderson and Inouye 2001). We postulated that such diversity would help ensure the functional integrity of a protective cap under threats from insect or pathogen outbreaks or disturbances such as fire. Furthermore, regardless of the kind of plants that are initially planted on a waste cap, common native species such as sagebrush (*Artemisia tridentata*) and rabbitbrush (*Chrysothamnus* sp.) likely will occupy the site eventually (Link et al. 1994). Hence, it is important to understand how a mixture of different species and different growth forms will perform. A mixture of 12 native species, including five shrubs, five perennial grasses, and two forbs was included as the second vegetation type in the experiment.

Objective 4. To compare the performance of a community of native species on ET caps to that of caps vegetated with a monoculture of crested wheatgrass.

1.2 Climate and Vegetation of the INEEL

The INEEL occupies some 2315 km^2 of the western edge of the upper Snake River Plain in southeastern Idaho, USA (43^o N, 112^o W). Average elevation of the area is about 1500 m. Mean annual temperature is 5.6^{o}C, and the frost-free period averages about 90 days. Characterized by high-magnitude diurnal and seasonal temperature fluctuations, the climate is typical of that of the region occupied by sagebrush steppe (West 1983, Caldwell 1985, Smith et al. 1997). During summer, low humidities and clear skies result in high temperatures and high evaporative demand during the day and relatively low temperatures at night due to rapid radiational cooling. Winters are cold, with several months having mean temperatures below freezing. Snow cover may persist for periods of a few weeks to over 2 months.

The INEEL lies in the rain shadow of the numerous mountain ranges of central Idaho. Average annual precipitation is 220 mm (Figure 2); however, there is substantial year-to-year variation in both annual and growing season precipitation, with total water-year precipitation varying from 72 mm to 342 mm in the past century (Figure 3). Precipitation tends to be uniformly distributed throughout the year, except for a peak early in the growing season (Figure 2). On average, 37% of the annual precipitation falls during April, May, and June; May and June are the wettest months (Figure 2). Melting snow and spring rains account for most of the annual recharge of moisture into the soil (Caldwell 1985, Anderson et al. 1987). In a typical year, most of the water available to plants is depleted by early to mid summer (Anderson et al. 1987). The predictability of the annual cycle of moisture availability has apparently selected for similar patterns of water use among the dominant species (Caldwell 1985, Anderson et al. 1987).

The Upper Snake River Plain is quite windy, especially during the growing season. Winds are primarily from the southwest, a result of the orientation of the Upper Snake River Plain with respect to surrounding mountains, which channel the prevailing westerlies (Clawson et al. 1989). Northeast winds frequently occur at night in response to rapid radiational cooling and down-slope air drainage. Monthly mean wind speeds at 6 m above the surface, recorded at the Central Facilities Area, range from a low of 8 km/h in December to 15 km/h in April and May (Clawson et al. 1989). The highest hourly average recorded was 82 km/h in March; peak gusts up to 126 km/h have been recorded (ibid.).

Surface features at INEEL reflect a long history of volcanic activity (Nace et al. 1972). Most of the area is a relatively flat plain, but the terrain is frequently broken and undulating because of underlying Quaternary basalt flows. Most soils are of aeolian origin derived from older silicic volcanics and Paleozoic sedimentary rocks from the surrounding mountains (McBride et al. 1978). Soils are primarily orthidic Aridisols, with Calciorthids being the most common great group.

Anderson et al. (1996) provide a general description of the vegetation and a complete flora. The natural vegetation at the INEEL typically consists of a shrub overstory with an understory of perennial grasses and forbs (herbaceous plants other than grasses and sedges). The dominant shrub is Wyoming big sagebrush (*Artemisia tridentata* subspecies *wyomingensis*). Basin big sagebrush (*A. tridentata* subspecies *tridentata*) may be dominant, or co-dominant with Wyoming big sagebrush, on sites having deep soils or sand accumulation (Shumar and Anderson 1986). Threetip sagebrush (*A. tripartita*) is common at higher elevations on alluvial slopes. Other important shrubs include winterfat (*Krascheninnikovia lanata*), green rabbitbrush (*Chrysothamnus viscidiflorus*), spiny hopsage (*Grayia spinosa*), prickly phlox (*Leptodactylon pungens*), horse-brush (*Tetradymia canescens*), and broom snakeweed (*Gutierrezia sarothrae*).

Common native grasses include thick-spiked wheatgrass (*Elymus lanceolatus*), bottlebrush squirreltail (*E. elymoides*), Indian ricegrass (*Achnatherum hymenoides*), and needle-and-thread (*Hesperostipa comata*). Bluebunch wheatgrass (*Agropyron spicatum*) is common at higher elevations, especially on alluvial fans and the slopes of the buttes. Great Basin wildrye occurs, often in nearly pure stands, on deep soils between lava ridges; it also is found in areas where sand accumulates or on disturbed sites such as mounds resulting from rodent burrowing.

Compared with much of the sagebrush steppe region, the INEEL supports a high diversity of forbs (Anderson et al. 1996). Some common native forbs are tapertip hawksbeard (*Crepis acuminata*), Hood's phlox (*Phlox hoodii*), false yarrow (*Chaenactis douglasii*), globe-mallow (*Sphaeralcea munroana*), bastard toadflax (*Comandra umbellata*) and various milkvetches (*Astragalus* sp.), buckwheats (*Eriogonum* sp.), paintbrushes (*Castilleja* sp.) and mustards (*Arabis* spp., *Stanleya viridiflora*, and *Lappula redowski*).

Numerous introduced annual and biennial species occur at the INEEL (Anderson et al. 1996). In 1995, those species contributed 11% of the vegetative cover on long-term vegetation plots at the INEEL (Anderson and Inouye 2001). Invasive weeds are among the most common of these introduced species. These include cheatgrass (*Bromus tectorum*), tumbling mustard (*Sisymbrium altissimum*), and Russian thistle (*Salsola kali*). Potential problems posed by these species to the performance of ET caps are addressed in section 4.7.

2.0 METHODS

2.1 Concepts, Terminology, and Calculations

Units of Measurement. Precipitation and ET are typically expressed as depths of water, in millimeters (mm) or inches (in.). The amount of water in the soil is commonly expressed as a percentage of the total soil volume. Soil water content can be estimated by weighing a soil sample before and after drying and then calculating the percent water by weight. This value is then multiplied by the bulk density of the soil (its undisturbed mass per unit volume) to convert percent water to a volume basis, referred to as volumetric water content. It is often convenient to express the amount of water in a soil profile as a depth of water in the same unit used for precipitation or ET. Percent water on a volumetric basis is readily converted to depths. For example, if a soil contains 30% water by volume, a meter depth of that soil will contain 300 mm of water.

Water Storage Capacity of Soil. Consider soil in which the upper part of the profile has been saturated with water and this overlies a relatively dry, unwetted zone. At first, redistribution of water within the profile is quite rapid because strong “suction gradients” from the dry soil augment the gravitational forces (Hillel 1998). With time, however, the downward flux slows as the suction gradients diminish and hydraulic conductivity of the soil decreases (Campbell and Norman 1998, Hillel 1998). Hysteretic phenomena, resulting from the interaction of sorption and desorption at the ***wetting front***, further inhibit redistribution, causing the wetted zone to retain more water than would be expected at equilibrium (Hillel 1998). The overall result is a logarithmic decrease in the rate of distribution with time so that after several days the water content of the wetted zone becomes relatively constant. The amount of water remaining in the profile at that quasi constant state, assuming that no water has been removed by ET, is referred to as ***field capacity***. Hillel (1998, p. 465) stresses that field capacity is not an “intrinsic physical property” of a soil; redistribution is continuous and “exhibits no abrupt ‘breaks’ or static levels.” Thus, the decision of when the downward flux of water has become negligible is subjective. Despite these difficulties, however, reliable estimates of an operational field capacity can be made using repeated measurements of soil-moisture content with depth *in situ*. (See Hillel [1998, Chapter 16] for a thorough discussion of these concepts.)

Plants differ in their capacity to extract water from a drying soil (Ritchie 1981). Perennial species native to arid regions may dry a soil more completely than will crops or species found in wetter areas. The extent to which a particular species depletes soil moisture is termed the ***lower limit of extraction***. The lower limit of extraction is estimated from the amount of water remaining in the soil when plant growth and activity completely stop (Ritchie 1981). Water remaining in the soil at that point is bound so tightly to soil particles that plants cannot remove it. Although water will continue to drain from a soil until it is completely dry (Campbell and Norman 1998), at the lower limit of extraction, hydraulic conductivity of the dry soil is so low that percolation is negligible (see section 3.3). Anderson et al. (1987) found that the lower limit of extraction was very similar for drought adapted species growing at the INEEL.

The difference between field capacity and the lower limit of extraction is the ***effective water-storage capacity*** of a soil. For example, if a soil has a field capacity of 30% water by volume and plants extract water to a volumetric content of 10%, the storage capacity is 20% by volume. If that soil were a meter in depth, it could store 200 mm of water. Field capacity and the lower limit of extraction depend on soil texture, type of clay present, organic matter content, soil structure, and the kinds of plants present. Therefore, estimates of these values must be made *in situ* (Ratliff et al. 1983).

The Water Balance Equation. Water entering an ecosystem must be equal to that leaving plus the change in the amount stored in the soil or biota. Consider the water balance of a small plot of land (Figure 1). Water reaches the plot as precipitation (**P**) or as surface runoff from adjacent areas ($\mathbf{R_i}$). (We will ignore springs and groundwater moving to the surface). Water leaves the plot by **ET**, by surface runoff from the plot to adjacent areas ($\mathbf{R_o}$), or by groundwater drainage (**G**). If inputs are greater than outputs, or vice versa, the amount of water stored in the soil (**S**) will change (D**S**). Thus, the water balance equation is merely a detailed statement of the law of conservation of matter.

These terms can be combined into a simple expression for the water balance of the plot:

$$P + R_i = ET + R_o + G + \Delta S$$

All of the units are expressed as mm of water per unit time.

On relatively level sites having porous soils, surface runoff is negligible so that the terms R_i and R_o can be ignored. If no water passes below the rooting zone, G is equal to zero. Hence, the water balance equation then becomes:

$$ET = P + \Delta S$$

We used this simplified form of the equation to estimate ET from the PCBE experimental plots. We emphasize that we used water balance only to estimate the magnitude of potential ET from vegetated caps under the semiarid climate of the INEEL.

Capillary Break. A capillary break is formed when a layer of fine-textured soil overlies a layer of coarse-textured sand or gravel. The matrix potential of the fine-textured soil prevents water from flowing into the larger pores of the sand or gravel until the fine soil approaches saturation at the interface (Hillel 1998). The gravel/cobble biobarriers used in the PCBE create a capillary break at the bottom of the overlying soil.

2.2 Experimental Design and Plot Layout

The Protective Cap/Biobarrier Experiment (PCBE) was a field-scale experiment, consisting of three replicates of four cap configurations, two vegetation types, and three irrigation treatments. To address Objectives 1 and 2, performance of two cap configurations with biobarriers at different depths was compared with that of caps consisting of soil only and with a cap based on RCRA recommendations. Objective 3 was addressed by comparing cap performance under ambient precipitation with that under augmented fall/spring and augmented summer precipitation. Performance of crested wheatgrass monocultures was compared to that of a diverse community of native species to meet PCBE Objective 4.

The 4 x 2 x 3 factorial experiment was arranged in a linear array (Figure 4). Each replicate consisted of four, 16- x 24-m **main plots** representing the four cap configurations (described below). Main plots were divided into six, 8- x 8-m **subplots**, representing the two vegetation types and three irrigation treatments (Figure 4).

The PCBE was designed for strip, split-plot analysis of variance (ANOVA; see Limbach et al. 1994). However, because of the low number of replicates and variability among them, that ANOVA design had very low power, resulting in a high probability of Type II errors (i.e., failure to find differences among caps, irrigation treatments, or vegetation types when they existed). To increase power and decrease the probability of Type II errors, we analyzed the experiment as a completely random design, using one-way and two-way ANOVA's. We acknowledge that this approach violates the assumptions of independence and random assignment of treatments among subplots, increasing the probability of Type I errors, but identifying *potential differences* in performance among caps or vegetation types is more important than being certain of a particular alpha level. Furthermore, cap locations and irrigation treatments were randomly assigned within replicates, vegetation types were randomly assigned within cap x irrigation treatments, and all plots were constructed at the same time, in the same area, and using the same fill soil (see below). Thus, departure from a completely random design was relatively minor. We also emphasize that if no statistical difference in performance was found using the completely random design in an analysis, one can be reasonably confident that performance among caps or vegetation types was indeed similar (i.e., if differences exist, they would not be large). All statistical analyses were completed using Stat32 (SPSS, Inc., Chicago, Illinois). $P = 0.05$ was generally used to indicate significance, but we report marginally significant results where deemed appropriate. The Tukey test (Zar 1999) as implemented in Stat 32 was used for multiple comparisons among means in both one-way and two-way ANOVA's. An alpha level of 0.05 indicated statistical significance for the Tukey test.

Two premises have guided the design of the ET caps in the PCBE. The first is that if the caps function as expected, no provision for drainage should be necessary; i.e., all of the precipitation water received will be returned to the atmosphere via evapotranspiration. Therefore, surfaces of the experimental caps are level, as are surfaces of intrusion barriers placed within caps (see section 2.3 for cap descriptions).

The second premise is that erosion will be minimized and side slope problems eliminated if waste caps are on grade with the area surrounding the caps. We understand that this may not be possible if caps are placed over existing waste sites, but it should be a consideration in the design of any new burial sites. The surfaces of our experimental plots are at the same elevation as the surrounding terrain.

2.3 Cap Configurations

Four cap configurations were included in the experiment (Figure 5). The rationale for each cap and its design details are as follows:

Soil-only Cap. This cap consisted of 2.0 m of compacted fill soil (Figure 5). This configuration was based on earlier research at the INEEL which demonstrated that a 2 m soil cap should be adequate to preclude moisture from reaching buried wastes (Anderson et al. 1987, 1991, 1993).

Shallow Biobarrier Cap. This cap included a biological intrusion barrier at a depth of 0.5 m within a 2-m soil profile (Figure 5). The biobarrier consisted of 0.3 m of river cobble (100 – 200 mm in diameter) sandwiched between 0.1-m layers of chipped gravel (5 – 15 mm in diameter). The purpose of this configuration was to assess the effects of a relatively shallow biobarrier on soil moisture dynamics and plant rooting depths. It was assumed that moisture received as precipitation would percolate below the biobarrier quite frequently, even under ambient precipitation.

Deep Biobarrier Cap. This cap included an intrusion barrier at a depth of 1 m within a 2-m soil profile (Figure 5). The biobarrier was identical to that of the shallow biobarrier cap. This cap was designed to assess the effects of a relatively deep biobarrier on soil moisture dynamics and plant rooting depths. In this case, we assumed that the depth of soil above the biobarrier would be adequate to store the ambient precipitation received in most years.

RCRA Cap. This design was based on Environmental Protection Agency guidelines (USEPA 1989) for implementation of the hazardous waste disposal regulations in the Resource Conservation and Recovery Act of 1976 (RCRA). For semi-arid areas, the EPA recommended a minimum of 0.6 m of soil overlying a sloped FML and a 0.6-m deep compacted clay layer. Our previous research showed that 0.6 m of soil would be inadequate to store ambient precipitation received during many years, so we increased the depth of soil overlying the FML to 1 m (Figure 5). The compacted clay layer and FML were emplaced with a 3% slope so that water would be transported off the cap once the soil above the FML was saturated.

2.4 Soil Characteristics

All experimental plots were constructed from the same fill soil, a silty clay loam soil obtained from Spreading Area B at the INEEL. The soil is a xerollic calciorthid consisting, on average, of 19% sand, 48% silt, and 33% clay. Soil texture did not differ statistically among replicates, but there was considerable variation among plots, with plot means for clay content ranging from 24% to 40% (Figure 4). Clay content of plots 7, 10, and 11 was well below that of the other plots. The variability in soil texture reflects variability in sediment deposition of the source soil.

2.5 Plot Construction

The PCBE was constructed by a private contractor between June and November, 1993 at the INEEL Experimental Field Station. A trench 320 m in length and 33 m wide was excavated to accommodate the plots. The trench was excavated to a depth of 1.8 m for the RCRA cap plots, to 2.7 m for the biobarrier cap plots, and to 2.2 m for the soil-only cap plots. The bottom of the trench consisted of local gravel in most places, but a portion of a few plots rested directly on basalt.

Six caissons, constructed from 3.11-m diameter and 4.87-m long galvanized steel culverts were set on end between pairs of main plots to accommodate drain lines from the RCRA caps and from drain pans positioned beneath all subplots. Caissons were emplaced on concrete pads 4.3 m below the soil surface. Each concrete pad included a 100-mm diameter floor drain over a gravel drain pit. Caissons were fitted with a sheet metal lid containing an access hatch and a ladder equipped with a notch rail system for fall protection.

Three 1.3-m diameter drain pans were placed under each subplot and were connected in series to adjacent caissons using schedule 40, 25.4-mm PVC pipe. Drain pans had a 0.3-m lip, and sloped to a depth of 0.5 m at the center. Gravel was placed in each pan to within 0.1 m of the top of the lip; the gravel was covered with geotextile to prevent siltation and clogging. Drain lines were directed to large plastic bins in the caissons where the volume of water received from a subplot could be measured.

Drain lines were also installed from the RCRA caps to the caissons. At the edge of each RCRA cap adjacent to a caisson, a loop was formed in the FML to catch any water draining from the soil/FML interface. A perforated 0.1-m PVC drainpipe was placed along the width of the subplot within the FML loop. The perforated pipe was then connected into the caisson with solid, 0.1-m pipe and directed to a plastic bin where runoff from the FML could be measured.

Each main plot was constructed in lifts of about 0.2 m and then compacted. Soils were compacted to a bulk density of approximately 1.29 g/cm^3. The clay soil underlying the FML on the RCRA plots was compacted to achieve a hydraulic conductivity of 1 x 10^{-7} cm/sec or less. A neutron hydroprobe access tube (20 gauge aluminum, 50.8 mm ID) was installed in the center of each subplot. Access tubes extend from the bottom of the plot to 0.2 m above the soil surface.

The FML on the RCRA cap plots was manufactured with sleeves to accommodate the access tubes. When the compacted clay layer was completed, access tubes were installed in holes drilled with a soil corer. The FML was then installed and a rubber gasket was placed around the sleeve to prevent water from flowing along the access tube into the compacted clay layer.

On the biobarrier plots, access tubes were installed using a soil corer when the soil underlying the biobarrier was in place. The gravel/cobble layers and the soil above the biobarrier were then constructed, taking care not to damage the protruding aluminum tubes. On the soil-only plots, access tubes were installed using a soil corer after the plots were completely constructed.

2.6 Vegetation Types.

Crested Wheatgrass Monoculture. "Nordan," a cultivar of crested wheatgrass, was drill-seeded at 6.7 kg/ha in rows 0.36 m apart at the recommended seeding depth of about 20 mm. Planting was done in early March, 1994. A gravel mulch creating about 75% ground cover was placed on the plots after they were seeded.

Native Vegetation. The native community established on the PCBE plots consisted of 12 species, including five shrubs, five perennial grasses, and two forbs (Table 1). Common shrubs and grasses were transplanted from local sagebrush communities onto the PCBE in mid-November, 1993. Small plants were hand excavated with their root-soil masses intact and transported in plastic pots. All transplants came from areas within about 2 km of the PCBE. Transplants were placed into a 0.75- x 0.75-m grid pattern on each subplot. Growth forms were alternated within rows (shrub, grass, shrub, etc.) so that each subplot was as homogeneous as possible. Within each growth form, five individuals were arranged so that each individual was at the center of a 1.5- x 1.5-m square and surrounded by individuals of the other four species, one at each corner (except for subplot borders). This planting arrangement ensured that conspecifics were never closer than about 2.3 m, adjacent individuals of the same growth form were about 1 m apart, and adjacent individuals of the other growth form (shrub or grass) were at a distance of about 0.75 m. These spacing patterns were based on plant densities in natural sagebrush communities in the area.

Two species of forbs were drill seeded into rows midway between the transplant grid rows in early March 1994. Commercially obtained seeds of 'Apar' blue flax (*Linum perenne*) were drilled in rows parallel to the 16-m sides of main plots at a density of 1.66 kg/ha (about 100 seeds/m^2). The second forb planted was northern sweetvetch

(*Hedysarum boreale*). About 0.5 kg of native sweetvetch seeds were collected about 20 km north of the Experimental Field Station at INEEL during the summer of 1993. However, this quantity was insufficient for our needs, so 1 kg of seeds was purchased to supplement the native seeds. Sweetvetch was drilled in rows parallel to the 24-m sides of main plots at a density of 7.7 kg/ha (about 50 seeds/m^2). Following planting, all subplots received gravel mulch covering about 75% of the surface. Shrub and perennial grass transplants that did not survive were replaced during 1994 (see section 3.1).

2.7 Irrigation System.

Supplemental water was applied to the PCBE plots with a drip irrigation system, which allows for precise control and metering of the water applied. Drip line and emitter configuration is identical on all 72 subplots. Drip lines are composed of flexible 16-mm polyethylene tubing 8 m in length. Lines are approximately .5 m apart, so each subplot has 16 drip lines. Emitters were placed at .5-m intervals; each subplot contains 264 emitters, which deliver water at about 17.6 L/min. Six solenoid valves control irrigation of each irrigation x vegetation treatment within each replicate. Standard water meters (Master Meter[1], Longview, Texas) were used to measure the amount of water applied. The irrigation system became operational in August of 1995 (see section 3.1).

2.8 Irrigation Treatments

The three irrigation/precipitation treatments were 1) ambient precipitation 2) summer irrigation, and 3) fall/spring irrigation. Ambient plots received no supplemental irrigation after 1994, once plants were established. The summer irrigation treatment consisted of four applications of 50 mm of water at biweekly intervals beginning in mid June. This treatment simulated an increase in summer rainfall events that would tend to only wet surface layers of soil. The fall/spring irrigation treatment simulated an increase in fall, winter, or early spring precipitation, which would cause deep recharge of soil water. Plots receiving this treatment were first irrigated when the irrigation system became operable in August of 1995. At that time, 550 mm of water were applied to drive the wetting front to the bottom of the plots. This was done to assess cap performance when the soil storage reservoir was nearly full (see section 3.6). In subsequent years, 200 mm of water were applied as quickly as possible in early October or, in 2000, in early April.

2.9 Soil Moisture Measurements

Soil water content (% by volume, *q*) was estimated by neutron scattering (Schmugge et al. 1980) with Model 503 Hydroprobes (Campbell Pacific Nuclear Corp., Martinez, California). Gravimetric soil moisture measurements, taken from soil profiles adjacent to neutron access tubes, were used to calibrate one of the Hydroprobes (R^2 = 0.84; n = 84; see Anderson et al. 1987 for details). The second probe was calibrated against the first using data taken with both probes from numerous tubes on the same date

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[1] Use of brand names does not imply endorsement by the U.S. Department of Energy

($R^2 = 0.98$). Measurements were made at depths of 0.2, 0.4, 0.6, 0.8, 0.9, 1.1, and 1.2 m, and then at 0.2-m intervals to the bottom of the cap. Because of variability in the depths of some subplots due to the presence of underlying basalt, there is some variability of the maximum depth recorded for individual subplots within a cap type. Soil moisture was generally measured at biweekly intervals through the growing season, beginning in late March and continuing through early October. Intervals were sometimes longer toward the end of the growing season when most soil moisture was depleted.

The total amount of water in the soil profile (S, in mm), was estimated for individual access tubes for each sampling date as:

$$S = 2\,(1.5\,q_{0.2} + \Sigma q_i + 0.5 q_{0.9} + 0.5 q_{1.1} + \Sigma q_j)$$

where, $q_{0.2}$ is the volumetric water content (%) at a soil depth of 0.2 m and q_i is the volumetric water content at depths of 0.4, 0.6, and 0.8 m, $q_{0.9}$ and $q_{1.1}$ are volumetric water contents at depths of 0.9 and 1.1 m, respectively, and q_j is volumetric water content at 1.2m and subsequent 0.2-m depth to the bottom of the profile. Because water content at the soil surface is so variable and could not be estimated accurately with a neutron probe, we assumed a uniform water content from the surface to 0.2 m.

In 1999, one of the two neutron probes malfunctioned, occasionally giving spurious or highly variable readings. The problem was not properly diagnosed until early in the 2000 growing season. This probe was used to take data from the even numbered subplots. In some cases, we were able to correct the data or avoid using data that were obviously erroneous. In some cases, however, we had to use the 1999 data despite what appeared to be unusual variation in order to get estimates of seasonal changes in water content. Given that this was an isolated problem, and given the plethora of data available and the consistency of results, we are confident that this malfunctioning did not appreciably affect the results or conclusions of the study. Nevertheless, the reader may notice some unusual variability in some 1999 and 2000 data included in this report.

A time domain reflectometry (TDR) system (Topp et al. 1982, Brisco and Pultz 1992) was installed on all subplots of Replicate 2 to provide a system for continuous monitoring of soil moisture. Waveguides were placed at four depths on each subplot and connected to multiplexers, wave generators, and dataloggers in the two adjacent caissons. Regrettably, despite considerable effort and expense, we were unable to obtain consistent, interpretable data from the TDR system. Consultation with officials at Campbell Scientific (Logan, Utah), the company that furnished some of the components and software, indicated that the waveguides were picking up interfering signals from some unknown source. Because we were unable to resolve these problems, we have not included any of the TDR data in this report. It should be noted, however, that we are absolutely confident of the neutron-probe measurements, and we would have had to rely on the neutron-probe data in any case because only that technique provided data from all three replicates. Thus, while we were disappointed not to have the convenience of continuous measurements and the possibility of monitoring water movements during short time periods, lack of reliable TDR data did not jeopardize the project.

2.10 Meteorological Measurements.

A meteorological station was established at the PCBE in 1997. Data recorded include air temperature, wind speed and direction, relative humidity, irradiance, net radiation, and precipitation. These data were collected to support an anticipated comparison of various ET model predictions with PCBE empirical results. Unfortunately, financial support to complete the modeling effort was not forthcoming. We have included the meteorological data in the CD that accompanies this report in hopes that it might be useful to others.

2.11 Precipitation Data and Estimates

Precipitation data from the INEEL Central Facilities Area (CFA) are available from 1950 to present. To estimate INEEL precipitation prior to 1950, data from 1950 through 1990 for three neighboring locations (Arco, Blackfoot, and Idaho Falls) were used as independent variables in a stepwise multiple regression with actual CFA precipitation as a dependent variable. The independent variables that explained the greatest amount of variance in the actual INEEL precipitation were used to estimate precipitation from 1905 to 1949. This analysis was done for both water-year (October through September) and for growing season (April through July) precipitation. None of the three neighboring stations had data for 1944, so the monthly 1950-95 data from CFA were regressed against those from Pocatello (the nearest Snake River Plain station from which 1944 data are available) to predict 1944 CFA precipitation. The CFA data and estimates were used to depict long-term extremes and variability in precipitation. CFA is 8.9 km south of the PCBE site.

For the period of the PCBE covered in this report (1994-2000), data from Idaho Nuclear Technology and Engineering Center (INTEC) were used when data from the PCBE site were unavailable. INTEC is 4 km south of the PCBE site.

2.12 Soil Coring and Lithium Tracer Studies

In the fall of 1998, an AMS PowerProbe (HAZDecon, Dayton, Ohio) was used to extract soil cores from below the biobarriers of nine shallow biobarrier and five deep biobarrier subplots. Cores were extracted and stored in clear PVC tubes until they could be examined in the laboratory. Live roots were separated from the soil by hand, dried, and weighted. After soil cores were extracted, we installed PVC tubes into the core holes through which a dilute solution of lithium chloride was introduced to the soil in the summers of 1999 and 2000. Leaf tissues were collected from plants adjacent to the tubes (within 1 m) and from the same species on the opposite side of the subplot (> 5 m from the tube) in August of 2000. Lithium content of dried tissues was measured by USEPA Procedure 6020 (ICP-MS; Sound Analytical Services, Inc., Tacoma, Washington).

2.13 Assessing Cap Breakthrough

Breakthrough was defined as drainage of water from the bottom of the soil profile. Our plan was to assess breakthrough by monitoring water draining into caisson bins from the three drain pans underlying each subplot. However, examination of soil moisture profiles on plots that received heavy irrigation or that were flooded by meltwater from snow indicated that the drain pans were not a reliable technique for assessing drainage. We had assumed that the 0.1-m lip on the drain pans above the gravel/geotextile interface would provide sufficient head to overcome the capillary break at that interface; this proved not to be the case. In some cases, we did observe drainage from the pans, but in others, no drainage was observed when the neutron-probe data indicated saturation of the soil at the bottom of a subplot. A greenhouse experiment, conducted in 1999-2000, in which we mocked up replicate caps with a drain pan emplaced within a fill soil profile, demonstrated that as the soil became saturated above the gravel/geotextile interface, water simply ran around the pan rather than draining into it. Because the drain pans were set on top of the natural gravel at the bottom of the plots, the capillary break of the drain pans was approximately 30 cm higher than that at the bottom of the plots.

Because we could not rely on the drain pans to indicate breakthrough of a cap, we had to use the neutron-probe data to estimate when a subplot would drain. By examining soil moisture profiles, it is easy to determine when the wetting front reaches the bottom of a cap. Because most plots were underlain by natural gravel that would create a capillary break, we assumed that no drainage would occur so long as the moisture content at the bottom is below field capacity for that soil. Our estimate of field capacity for this soil is 28% moisture by volume (see section 3.3). Therefore, we used 28% volumetric water content at the bottom of a profile to indicate potential breakthrough of the cap on a subplot.

2.14 Irrigation to Breakthrough Trials

In April and May of 1999, we irrigated all fall/spring subplots until drainage was observed from the collection pans or the water content at the bottom of the plot was estimated to be at or above field capacity (≥ 28%; see section 3.3). For these trials, irrigation was applied as rapidly as possible without causing pooling of water on the plots. We compared 1) the amount of water added before drainage occurred and 2) the amount of water in the total soil profile when drainage occurred among cap and vegetation types.

2.15 End-of season Soil Moisture Comparisons.

Volumetric water content measured in mid to late September was used to estimate the lower limit of extraction of soil moisture by the vegetation. Because end-of-season moisture content indicates the extent to which the water storage reservoir has been emptied, we compared end-of-season water content among cap types, vegetation types, and irrigation treatments. These comparisons included mean water content in the total profile, water content of the top meter of soil among the soil-only, deep biobarrier, and RCRA caps, water content of the top half meter of soil for the soil-only and shallow biobarrier caps, water content of the bottom meter of soil between the soil-only and deep biobarrier caps, and water content of the bottom 1.5 m of soil between the soil-only and shallow biobarrier caps.

2.16 Data Presentation and Interpretation of Soil Moisture Profiles

Measuring soil moisture content on 72 subplots at 10 to 12 depths biweekly during six growing seasons generated a very large amount of data. We have analyzed annual soil-moisture dynamics for each subplot by plotting data for eight dates. Because it is infeasible to include all of those results in this report, we present representative soil-moisture profiles for each cap type by irrigation combination across the 6 years of study. We also show seasonal profiles for all subplots of each cap type X irrigation combination for one year to illustrate variability among replicates. We chose 1998 to illustrate this variability because precipitation during the 1997-1998 water year was very near the long-term average for the INEEL. The distribution of the 1998 precipitation also was typical of long-term averages, with wet months of May and June followed by a dry summer (Figure 6). We included additional profiles as needed to illustrate specific points.

Soil moisture profiles (Figures 10 – 37) depict the vertical distribution of moisture in the soil on various sampling dates. Each line shows volumetric soil moisture content as a function of depth for a particular sampling date. Differences in line position from date to date reflect the magnitude of change in moisture storage in the soil column. As moisture is extracted over the growing season, lines for consecutive dates move leftward across the graph. An increase in water storage is indicated by the profile line moving to the right from one sampling date to the next. When the position of lines from one sampling date to the next are virtually unchanged at particular depths, no appreciable change in moisture storage has occurred.

Constant water content at some soil depth does not mean that no flow is occurring through that depth. Flow is driven by a gradient in total hydraulic head, not a gradient in water content (Benson et al. 2001). The percolation rate will equal the hydraulic conductivity of the soil at the existing water content (ibid). Hydraulic conductivities and percolation rates vary by orders of magnitude depending on water content. When soils are relatively dry (e.g., near the lower limit of extraction), hydraulic conductivities are very low (10^{-10} to 10^{-12} cm/s) (Campbell and Norman 1998, Benson et al. 2001). Therefore, constant, low water contents at depth in a soil profile indicate that percolation would be negligible (see section 3.3).

3.0 RESULTS

3.1 Precipitation During Study, Vegetation Establishment, and Initial Soil Moisture Dynamics

During the period of this study (1994-2000), water-year (October – September) precipitation, recorded at INTEL, ranged from a low of 129 mm in 1999-2000 to a high of 318 mm in 1994-1995 (Figure 6). The period included near extremes for the period of record at INEEL (1950 – 2000), representing well the recorded climate variability of the area (Figure 3). The 1994 – 1995 water-year stands out as exceptionally wet, the highest on record for the INEEL with 342 mm measured at Central Facilities Area. This is 34 mm higher than the next highest water-year total (308 mm) recorded in 1968. Precipitation in May was above normal, and record amounts of rain fell in June (118 mm; Figure 6). In contrast, the 1993 – 1994 and 1999 – 2000 water years were very dry (Figure 6), with very little precipitation in June, normally the wettest month (Figure 2).

Low precipitation in 1994 created unfavorable conditions for establishment of vegetation on the experimental plots. Mean soil water content at the beginning of the growing season ranged from 14% to 21% and averaged only 17%. No precipitation fell during March, precipitation in May was well below normal, and virtually no rain was received during June and July (Figure 6). As a consequence of the dry season, mean survival of shrubs that had been transplanted onto the plots in late fall, 1993, was only 55.4%, and that of grasses was only 65.9%. We transplanted 1,054 shrubs and 783 grasses in 1994 to replace those that had died. Because the experimental irrigation system was not yet in place, we applied supplemental water periodically during the summer of 1994 with an old sprinkler system consisting of aluminum "hand lines". Precise control of amounts applied was impossible, so the amounts received by individual plots was quite variable but sufficient to prevent further mortality of transplants and ensure germination and establishment of the seeded species. By the end of the 1994 growing season, vegetation was established on all plots.

Supplemental irrigation in 1994 caused a spike in soil moisture during the summer, after which moisture was gradually depleted as plants became established and evapotranspiration increased (Figure 7A-C). By late August, moisture on many of the plots was as low as or below that at the beginning of the season. Some plots received additional irrigation in early September of 1994, but the amounts applied were highly variable resulting in the large error bars on the water content mean for some cap-type/vegetation combinations at the end of the 1994 growing season (Figure 7A-C). Natural precipitation received during the fall, winter, and early spring of 1994 – 1995 increased soil moisture on all plots; however, despite record rainfall in June of 1995 and an exceptionally wet growing season (Figure 6), most plant-available water had been extracted from the ambient and summer-irrigation plots by the end of the 1995 growing season (Figure 7A, B; see section 3.4, Performance of the Soil-only and Biobarrier Caps in 1995). Irrigation applied to the winter-irrigation plots in late summer of 1995 increased soil moisture on those plots (Figure 7C).

3.2 Vegetation Development

Plant cover on both native vegetation and crested-wheatgrass subplots developed rapidly after initial establishment. At the beginning of the 1995 growing season, plant cover on the native-vegetation subplots ranged from 10% to 13%; it doubled by the end of the growing season (Table 2). Cover on the crested-wheatgrass subplots was measured at the end of the 1995 growing season; it ranged from 36% to 48%, roughly double that on the native-vegetation subplots (Table 3). After the initial cover estimates in 1995, cover of crested wheatgrass was not measured again on all replicates until 2000. In the interim, cover on crested-wheatgrass plots had been reduced by about 50% (Table 3). This reduction was caused by high plant productivity in 1995 and 1996, which resulted in a lot of standing dead material and thick layers of litter that inhibited plant growth in subsequent years. The consequences of the reduced plant cover on crested-wheatgrass plots are presented in section 3.10.

Although cover on the native-vegetation subplots at the end of the 1995 growing season was about half that of the crested-wheatgrass subplots, it continued to develop rapidly, peaking in 1997 (Figure 8). Under ambient precipitation, total cover on the four caps has been remarkably similar throughout the study period (Figure 8). Cover on the ambient subplots in 1997 averaged 53% and subsequently decreased to 29% in 2000. Such fluctuations in cover are to be expected in response to year-to-year and longer-term variation in precipitation (Anderson and Inouye 2001). Mean cover of grasses + shrubs on long-term vegetation plots at the INEEL ranged from about 25% to 32% over the last three decades (ibid.). Thus, the cover values for 1998 – 2000 under ambient precipitation (Figure 8) are similar to those of natural sagebrush steppe at the INEEL (Anderson and Inouye 2001). The decrease in total cover after 1997 was a consequence of a large decrease in cover of perennial grasses and forbs; shrub cover has increased consistently through the study period (Figure 9).

Under summer irrigation, peak cover values in 1997 ranged from 55% to 79%, with the soil-only and deep biobarrier subplots having somewhat higher cover than the shallow biobarrier and RCRA subplots (Figure 8). However, by 2000, cover on all cap types was similar, averaging 39%. Thus, at the end of the study period, summer irrigated subplots maintained about 10% more vegetative cover than did subplots receiving ambient precipitation. Forb cover peaked in 1998 on the summer-irrigation subplots, but then decreased substantially, especially during the dry 2000 growing season (Figure 9). Nevertheless, forb cover remained considerably higher on the summer irrigated plots than on the ambient plots (Figure 9). As seen with the ambient vegetation plots, shrub cover has continued to increase over the study period (Figure 9).

Peak cover on fall/spring irrigated subplots ranged from 69% on RCRA subplots to 106% on deep biobarrier subplots (Figure 8). Subsequently, cover decreased considerably on all cap types. By 2000, cover was similar on the soil-only and biobarrier subplots, averaging 51%, 12% higher than that on subplots receiving summer irrigation. Cover was lower ($p = 0.069$) on the RCRA subplot (36%), reflecting the difference in soil depth available to store water. Mean cover on the RCRA subplots in 2000 was identical under summer and fall/spring irrigation. Both forb and perennial grass cover peaked in 1997 under fall/spring irrigation and subsequently decreased, although, unlike results on the ambient precipitation and summer-irrigated subplots, grass cover increased in 2000 (Figure 9). As seen under the other treatments, shrub cover has steadily increased under fall/spring irrigation (Figure 9).

Why do native-vegetation subplots receiving fall/spring irrigation maintain higher cover than those receiving summer irrigation when both treatments receive 200 mm?

More water is available to plants under fall/spring irrigation because direct evaporative loss is less than under summer irrigation, which is applied in small (50 mm) increments at two-week interval when temperatures are high.

3.3 Estimates of Field Capacity and Lower Limit of Extraction

Examination of soil moisture profiles following precipitation or irrigation events indicates that field capacity for the PCBE soil is about 28% moisture by volume (see e.g., Figures 10, 19, 29, 33), the same value determined experimentally for soils from the same source in an earlier study (Anderson et al. 1991). Estimates of the lower limit of extraction, based on moisture remaining in the soil of native-vegetation plots under ambient precipitation at the end of the growing season, typically were 14 – 16% (Table 4). These estimates are based on the entire soil profile, and, in most years, did not differ among cap types. The top 0.5 or 1 m of soil often had end-of-season water contents between 11% and 14%, but to estimate the capacity of the storage reservoir, the average content of the entire profile was used. Given a field capacity of 28% and 15% as the lower limit of extraction, the effective storage capacity is 13% by volume. Thus, a 2-m soil profile could store 260 mm of water.

Anderson et al. (1987) measured water potential of vegetated soils from the same source as the PCBE soil. At the lower limit of extraction, water potentials in the upper 1 m of soil typically were about -3 MPa (-30 bars), while those in the bottom meter of soil were from -1.0 MPa to -1.5 MPa (-10 to -15 bars). To assess the potential for water to drain from these dry soils according to Darcy's Law, we used equation 9.2 and parameter estimates for a silty clay loam soil in Table 9.1 of Campbell and Norman (1998) to estimate hydraulic conductivity. Hydraulic conductivity varied from 3.4×10^{-11} cm/s at a water potential of -1.0 MPa to 2.3×10^{-12} cm/s at a water potential of -3.0 MPa. These values are four to five orders of magnitude lower than the 10^{-7} required for a compacted clay layer in a RCRA cap (USEPA 1989). Clearly, a negligible amount of water would drain from the PCBE soil at the lower limit of extraction by plants.

3.4 Performance of the Caps under Ambient Precipitation

Under ambient precipitation, the soil-only cap and the two biobarrier caps generally performed similarly. In the vast majority of cases, the wetting front never reached the bottom of a cap, and all moisture received was returned to the atmosphere via evapotranspiration. Representative examples of soil moisture dynamics on a native-vegetation subplot of each cap type are shown in Figures 10 – 13.

Soil-only Cap. Over the six years shown, the depth to which the wetting front reached on the soil-only plot varied from less than 0.2 m in 2000 to over 1.2 m in 1995 and 1999 (Figure 10), reflecting the variability in precipitation received (Figure 6). In all years, all of the water available to plants was extracted by the end of the growing season.

In the spring of 1999, soils on two of the soil-only subplots and one deep biobarrier subplot (discussed below) became saturated and drained when they were flooded by runoff from adjacent areas during snowmelt in March (Figure 14). These were the only cases of cap breakthrough under ambient precipitation during the study. Moisture profiles for the replicate caps demonstrate that they can readily store the precipitation received if run-on and pooling of water on the surface is avoided (1999 data in Figures 10 and 12). On the soil-only, crested-wheatgrass plot that drained, sufficient moisture had been extracted by the end of the growing season to reduce water content at the bottom of the profile below field capacity (Figure 14A). On the native-vegetation subplot, virtually all of the plant available water was used throughout the entire soil profile, reducing water content to the same levels as existed in the fall of 1998 (Figure 14B). Growing season evapotranspiration from this plot was 346 mm. In 2000, crested wheatgrass plants extracted water from the entire profile, but there was still substantial water deep in the profile at the end of the growing season (Figure 14D). In contrast, on the native-vegetation subplot there was virtually no change in water content below 0.6 m on 2000 (Figure 14E). These results clearly demonstrate that a healthy stand of native perennial plants can use all of the plant available water in 2 m of saturated soil. Thus, should a portion of a soil-only cap become saturated due to local pooling or subsidence, the vegetation can reset the storage capacity of that cap within a single growing season.

Figure 15 depicts the variability among replicate soil-only caps under ambient precipitation in 1998, a year in which water-year precipitation was right at the long-term average and in which May and June were typically wet followed by a dry summer (Figure 6). In this case, there was essentially no recharge of soil water over the winter on five of the six subplots, but one native-vegetation subplot showed a substantial increase with the wetting front reaching nearly 0.8 m by 5 March (Figure 15). Snowmelt and precipitation received between 5 March and 22 April increased water content similarly on most of the other subplots. Figure 15 and similar ones that follow for the other cap-type/irrigation combinations demonstrate the importance of replication. Responses vary among replicates because of a myriad of uncontrolled factors (e.g., the placement of the neutron access tube in a subplot in relation to microtopography and characteristics of plants in the immediate vicinity, local variation in soil texture and microtopography). Without replication, one cannot determine whether an observed difference among cap-types, for example, is due to cap configuration or to some uncontrolled factor.

Shallow Biobarrier Cap. For the shallow biobarrier plot shown in Figure 11, water percolated below the biobarrier only in 1999, when the wetting front reached 1.6 m (but only 1.1 m in soil if the 0.5-m biobarrier is ignored). All of that water was extracted by the end of the growing season. Under ambient precipitation, water percolated below the shallow biobarrier on all three crested-wheatgrass subplots and on one native-vegetation subplot in 1995 (see further discussion of soil moisture dynamics in 1995 below), on one native-vegetation subplot in 1997, on one crested-wheatgrass subplot in 1998 (Figure 16), on two crested-wheatgrass and two native-vegetation subplots in 1999, and on no subplots in 2000. Thus, in all but one of the study years, water moved into the soil below the biobarrier on at least one shallow biobarrier subplot. Figure 16 depicts the variability among replicates typical of shallow biobarrier caps under ambient precipitation.

Deep Biobarrier Cap. Typically, there was no change in soil water content below deep biobarriers under ambient precipitation (Figure 12). Water percolated below the biobarrier in only two cases over the 1995 – 2000 period. In 1995, the wetting front reached a depth of 2.2 meters on one native-vegetation plot. Most of that water was extracted by the end of the growing season, and subsequently there has been no change in water content below the biobarrier on that subplot (data not shown). The second case, mentioned earlier, occurred in the spring of 1999 when subplot 9-6 was flooded by runoff from adjacent areas during snowmelt (Figure 14C). In that case, there was no evidence of extraction of water below the biobarrier in 1999, but in 2000 sufficient water was extracted below the biobarrier to reduce average moisture content to about 23%, well below field capacity (Figure 14F). The difference between the 20 September 1999 and 28 March 2000 profile lines indicates that some water drained from this plot during the 1999 – 2000 winter.

Figure 17 depicts typical variability among deep-biobarrier replicates. Note that one of the three replicates of each vegetation type showed much less water in storage early in the growing season than the other two replicates (plot 6, subplot 3 and plot 9, subplot 5).

Performance of Soil-only and Biobarrier Caps in 1995. In 1995, no irrigation treatments were applied prior to early August, when the fall/spring plots were irrigated. Therefore, we were able to evaluate the soil-moisture dynamics of all plots under ambient precipitation prior to that date. Under record water-year and growing-season precipitation, the wetting front reached the bottom of one soil-only and one shallow-biobarrier subplot following rainfall in late May and early June. The soil-only plot had relatively low vegetative cover. Water content at the bottom of the plot increased from 18% to 23%, remaining well below field capacity. By mid June of 1995, water had percolated below the shallow biobarrier on six of the twelve subplots, but in only one case did the wetting front reach the bottom of the profile. This subplot had received heavy irrigation in the fall of 1994, so the soil above the biobarrier was nearly saturated at the beginning of the 1995 growing season. Water content at the bottom of that plot reached 30% by 12 June and remained above field capacity through the remainder of the growing season. This is the only one of the 54 subplots comprising soil-only, shallow biobarrier, and deep biobarrier caps from which drainage may have occurred during this record precipitation year. By the end of the 1996 growing season, plants had extracted most of the available water below the biobarrier of that subplot, reducing soil moisture at the bottom of this subplot to 10% (data not shown).

RCRA Cap. Under ambient precipitation, the RCRA cap was inadequate to store the precipitation received in 1995, 1998, and 1999. The wetting front reached the FML liner on two of the three crested-wheatgrass subplots and on all of the native-vegetation subplots (e.g., Figure 13). Drainage from the liner occurred on subplots on one of the three replicates in 1995. In 1998, the wetting front reached the liner on one crested-wheatgrass subplot (Figure 18: plot 1, subplot 2), and in 1999 the wetting front reached the liner on two native-vegetation and two crested-wheatgrass subplots (e.g., Figure 13). With the exception of 2000, soil moisture early in the growing season approached field capacity to a depth of 0.8 m on some RCRA caps each year under ambient precipitation (Figures 13 and 18), indicating little reserve storage capacity before drainage from the liner would occur. As shown in Figure 18, considerable variability in soil moisture dynamics was observed among replicate crested-wheatgrass subplots on RCRA caps in some years.

Evapotranspiration and End-of-season Soil Moisture Content. Under ambient precipitation from 1995 through 2000, there was no significant difference in growing-season ET among cap types or between vegetation types, and there was no significant interaction between cap type and vegetation type in any of the two-way ANOVAs (Table 5). Mean ET ranged from 113 mm in 2000 to 338 mm in 1995. The value for 1995 is anomalously high since the total water-year precipitation for 1994-95 was 318 mm. The high value occurred because some of the PCBE plots had considerable residual moisture in the soil at the beginning of the growing season as a result of irrigation late in 1994; that residual moisture was extracted and transpired in 1995. The other contributing factor was that much of the record 1995 precipitation fell during the growing season (Figure 6) and was simply returned to the atmosphere via evapotranspiration.

Under ambient precipitation, there was no case of a significant difference in end-of-season soil moisture among cap types for the 1995-2000 period (Table 4). Overall yearly means for the native-vegetation plots ranged from 13.9% to 15.5% moisture and from 13.8% to 16.9% for crested-wheatgrass plots. The high value for crested wheatgrass occurred in 1999 and reflects failure of crested wheatgrass to use all of the available soil moisture because of reduced plant cover (see section 3.10).

3.5 Performance of the Caps under Summer Irrigation

The summer irrigation treatment was initiated in June of 1996. Representative examples of soil moisture dynamics on a native-vegetation subplot of each cap type are shown in Figures 19 – 22. Performance of the caps under summer irrigation was generally similar to that under ambient precipitation (cf. Figure 7a with 7b and Figures 10 – 13 with Figures 19 – 22). There was no difference in depths reached by the wetting front between subplots receiving ambient precipitation and those receiving summer irrigation ($P = 0.97$). The similarity between ambient precipitation and summer-irrigated plots reflects the fact that most water received during the growing season is returned immediately to the atmosphere, so long as plants remain active. Overall, the results indicate that a modest increase in summer precipitation, as predicted by some climate change models (see section 1.1), would have little impact on the performance on an ET cap.

Soil-only Cap. No breakthrough occurred on the soil-only subplots receiving summer irrigation during the study. In fact, the wetting front did not reach the bottom of any of the six subplots during the five years of treatment (e.g., Figure 19). Increases in moisture content following summer irrigation were detectable on all plots each year. These increases usually were limited to the upper 0.6 m of the profile (e.g., Figures 19, 23). Most of the water available to plants was extracted by the end of the growing season, so there was little difference in end-of-season moisture content between the ambient precipitation and summer irrigation treatments for either the native or crested-wheatgrass subplots (Table 4).

Shallow Biobarrier Cap. Under summer irrigation, no breakthrough occurred on the shallow biobarrier subplots after the summer irrigation treatments were initiated, and water percolated to the bottom of the soil profile in only one case, following snowmelt in 1999 (Figure 20). Water percolated below the biobarrier in three of six subplots in 1996, in one in 1997, in one in 1998 (Figure 24: plot 8, subplot 2), and in four in 1999. However, in all but one of these cases, that percolation occurred in the spring well before the summer irrigation treatments were applied. Thus, all of the summer irrigation water generally was stored in the 0.5 m of soil above the biobarrier and was completely extracted by the end of the growing season (e.g., Figures 20, 24).

Deep Biobarrier Cap. We observed little change in water content on the deep biobarrier subplots after the summer irrigation treatments were initiated (e.g., Figures 21, 25). Ambient precipitation as well as the supplemental water applied were stored in the meter of soil overlying the biobarrier, and most of the plant-available water above the biobarrier was extracted by the end of the growing season (Figures 21, 25).

RCRA Cap. As observed under ambient precipitation, the spring wetting front reached the FML liner on RCRA subplots in each year except the very dry 2000. However, summer irrigation did not cause runoff from the impermeable FML liner on any of the RCRA subplots during the five years of treatment (Figures 22, 26). Although the 1 m of soil above the FML was occasionally nearly saturated at the beginning of the growing season (e.g., Figure 22, data for 1999), sufficient water was extracted from that soil by the time summer irrigation commenced to allow storage and subsequent evapotranspiration of the supplemental water (Figures 22 and 26).

Evapotranspiration and End-of Season Soil Moisture Content. For the five years during which summer irrigation was applied, there was no significant difference among cap types in total growing season ET (Table 5). Vegetation types differed only in 1999 when ET was higher on native-vegetation than on crested-wheatgrass subplots (Table 5). ET ranged from 329 mm in 2000 to 407 mm in 1997 (Table 5). These values are, of course, much higher than those under ambient precipitation (from 1.7 to 2.9 times higher), reflecting the addition of 200 mm of water during the growing season.

We were unable to detect any statistical difference in end-of-season soil moisture between ambient and summer irrigation treatments on native-vegetation subplots (Table 6). Thus, addition of 200 mm of water during the summer did not decrease the size of the storage reservoir for the next water year for any of the cap types. In contrast, end-of-season soil moisture was significantly higher under summer irrigation than under ambient precipitation on crested-wheatgrass subplots in four of six years (Table 6). Mean end-of-season water content was higher on crested-wheatgrass subplots than on native subplots every year after the summer irrigation treatments were initiated (two-way ANOVA with cap type and vegetation type as factors, $P < 0.04$ in all cases; means shown in Table 4). Further analyses are given in the section 3.10.

3.6 Performance of the Caps under Fall/Spring Irrigation

Irrigation treatments on the fall/spring subplots were initiated in 1995 with the application of 550 mm of water between August 1 and August 14. This large amount of water was applied to force percolation of water to the bottom of the plots so that we could assess cap performance under a "worse case" scenario when the soil storage reservoir was completely full. Following that application of water, the wetting front reached the bottom of all but three of the 18 subplots representing the soil-only, shallow biobarrier, and deep biobarrier caps (Figure 27). Drainage from the pans underlying two of those subplots occurred, and moisture profiles indicated that soil moisture at the bottom of three other plots was above field capacity. Thus, despite adding 550 mm of water late in an exceptionally wet growing season, breakthrough occurred on only five of these 18 subplots. It should be noted, however, that sufficient plant cover was present and active to remove a substantial amount of the water added between August 14 and September 20, so moisture content in the upper 1 m of soil was well below field capacity by the end of the growing season (Figure 27). Soil moisture dynamics on three of these subplots during the next growing season (1996) illustrate the capacity of ET caps to recover storage capacity (Figure 28). Results from these subplots are discussed further in the sections that follow.

Growing season ET estimates for 1995 for the subplots that did not fail following the August irrigation ranged from 681 mm from a deep-biobarrier, crested-wheatgrass subplot to 818 mm from a deep-biobarrier, native-vegetation subplot. These values are close to a potential growing-season ET estimate of 790 mm, based on the Penman-Montieth equation (Monteith 1980) and 1997 micrometeorological data from the PCBE (Anderson et al. 1998).

Representative soil-moisture profiles for a native-vegetation subplot for each cap type under fall/spring irrigation are shown in Figures 29 – 32, and profiles depicting variability among replicates in 1988 are shown in Figures 33 – 36. These plots were also used for the irrigation to breakthrough trials in 1999 (see sections 2.14 and 3.9), so analyses here cover 1996, 1997, and 1998.

In August of 1996, six of the eight fall/spring irrigation plots of Replicate 3 were accidentally irrigated when a valve on the irrigation system was inadvertently left open. These included soil-only subplot 11-1, shallow biobarrier subplots 10-1 and 10-2, deep biobarrier subplots 9-1 and 9-2, and RCRA subplot 12-1. Water content at the bottom of all of these plots was above field capacity by the end of the 1996 growing season. Water content throughout the soil profile on all of these plots was reduced below field capacity by the end of the 1997 growing season. Figure 37 depicts moisture dynamics during 1997 and 1998 on these soil-only and biobarrier plots having native vegetation. Moisture content was reduced to 22% or less throughout the soil profiles by the end of the 1997 growing season (Figure 37), documenting the efficacy by which native vegetation can extract water and reset the storage capacity of saturated caps in a single season. Water content on the crested-wheatgrass subplots was also reduced below field capacity but was higher than that on the native subplots (data not shown; see section 3.10). The six plots that were accidentally irrigated are excluded from the analyses for 1996 that follow.

Soil-only Cap. During the 1996 growing season, plants extracted water from the entire soil profile on the Replicate 1 and 2 soil-only plots, reducing water content to 21% or less at the bottom of the profiles by the end of the growing season (e.g., Figures 28, 29). Following the heavy August 1995 irrigation, water content at the bottom of the soil-only subplot shown in Figure 28 was above field capacity at the beginning of the 1996 growing season. Water content at the bottom of the plot changed only slightly between March and mid July while water was extracted from upper portions of the soil profile. However, by 29 August water content at the bottom of the plot was reduced from over 30% to 21%, with most water consumed during that period coming from deep in the profile (Figure 28).

Fall irrigation in 1996, 1997, and 1998 typically caused percolation to a depth of 0.8 to 1.2 m in soil-only plots (Figure 29, frames for 1997, 1998, and 1999; Figure 33). Water from snowmelt and early spring rainfall pushed the wetting front to greater depths in those years, sometimes increasing water content in the soil at the bottom of a plot (e.g., Figure 29). Regardless of the amount of water applied, plants generally used most of the available water by the end of the growing season, essentially emptying the storage reservoir. An example is shown in Figure 29. Here, the irrigation to breakthrough trial in 1999 saturated the entire profile by May 20. Water was being extracted from the entire profile by July 15, and, by the end of the growing season, water content throughout the profile was below 19%.

Despite water content being below 20% throughout its profile at the end of 1996, the crested-wheatgrass subplot of Replicate 3 (Subplot 11-2) drained in 1997, 1998, 1999 (irrigated to breakthrough), and 2000 (e.g., Figure 33, upper right frame). This is the only case in the entire study where breakthrough occurred on a plot in consecutive years. We believe that this was a consequence of low moisture storage capacity on this subplot resulting from a clay content of only 24%. In any case, this occurrence was obviously an exception.

Shallow Biobarrier Cap. Plants extracted water from below the biobarrier on all of the shallow biobarrier plots in 1996 (e.g., Figures 28, 30), and end-of-season mean water content on the Replicate 1 and 2 subplots, in neither the total profile nor the bottom 1.5 m of the profile, was different from that in the soil-only subplots (Tables 4, 8). Thus, as for the soil-only subplots, the soil-moisture storage reservoir had been essentially emptied in one season.

Fall irrigation in 1996, 1997, and 1998 caused percolation through the shallow barrier on all subplots, but the wetting front reached the bottom of a subplot in only two cases during those three years (e.g., Figures 30, 34). As with the soil-only subplots, snowmelt and early spring rainfall sometimes pushed the wetting front to greater depths (e.g., Figure 30), but in no case did moisture content at the bottom of a Replicate 1 or 2 subplot reach field capacity. Water was extracted from below the biobarrier on all subplots. Native vegetation typically reduced water content throughout the profile to less than 20% (e.g., Figures 28, 30), but end-of-season moisture below the biobarriers on the crested-wheatgrass subplots was about 25% (e.g., Figure 34, see section 3.10).

Deep Biobarrier Cap. In 1996, water was extracted from below the biobarrier on two of the four deep biobarrier subplots in which the wetting front had reached the bottom of the plot in 1995. One of those is shown in Figure 28 (plot 6, subplot5), where water content at the bottom of the plot was reduced from above field capacity to about 21% by the end of the growing season. This figure demonstrates clearly that the change in water content below both biobarriers was due to extraction by plants and not to drainage, because water content below the biobarriers did not change until plants had extracted most of the plant-available water above the biobarriers. Had the change in water content below the biobarrier been due to drainage, change would have been seen at earlier dates. In the case of the deep biobarrier subplot, there is virtually no change in water content below the biobarrier between October of 1995 and 20 June 1996. By the latter date, most of the water available to plants had been extracted from the top 1 m of the profile; at the next sample date (16 July), there is evidence of removal of water below the biobarrier, and by the end of August, mean water content below the biobarrier was 20%. The seasonal pattern of extraction for the shallow-biobarrier subplot is similar (Figure 28).

Deep biobarrier subplots generally were capable of storing the 200 mm of water applied in the falls of 1996, 1997, and 1998 above the biobarrier, although in a few cases there was a slight increase in soil moisture below the biobarrier (e.g., Figures 31, 35). In some cases, snowmelt and early spring rainfall increased water content below the biobarrier, but, whenever that occurred, the water was extracted by the end of the growing season (e.g., Figure 31, frame for 1997). As seen with the shallow biobarrier plots, end-of- season water below the biobarrier was typically below 20% on the native-vegetation subplots and near 25% on the crested-wheatgrass subplots (Figure 35).

RCRA Cap. Following fall irrigation, the soil on RCRA caps typically was near saturation, so there was little reserve storage volume available to store winter and spring precipitation (Figures 32, 36). The wetting front reached the FML liner on many subplots each year (e.g., Figures 32, 36).

Evapotranspiration and End-of Season Soil Moisture Content. Growing season ET following irrigation the previous fall ranged from lows of 190 to 256 mm in 1996 to highs of 346 to 422 mm in 1997 (Table 5, cap means). In 1997, 1998 and 2000, there was no significant difference among cap types in ET. In 1999, ET was estimated for the period following the irrigation to breakthrough trials because we had no way to estimate drainage losses during those trials. In this case, ET was significantly lower from the RCRA cap than from the other three (Table 5). This result reflects the difference in storage capacity between the RCRA cap with 1 m of soil and the others with 2 m.

Following the irrigation to breakthrough trials, entire depths of soil were at field capacity, so there simply was much more water to extract from the soil-only and biobarrier caps.

On native-vegetation subplots, we found no significant difference in mean end-of-season soil moisture, measured prior to fall irrigation, among cap types in any year under the fall/spring irrigation treatments ($P > 0.45$ by one-way ANOVA; means shown in Table 4). Furthermore, the only difference in end-of-season soil moisture between subplots receiving ambient precipitation vs. fall/spring irrigation occurred in 1996 when Replicate 3 fall/spring subplots were accidentally irrigated in August (Table 6). Thus, on native-vegetation subplots, 200 mm of supplemental irrigation did not result in any accumulation of water in the soil caps.

On crested-wheatgrass subplots, there was a significant difference in end-of-season soil moisture among cap types in 1999, following the irrigation to breakthrough trials, when the RCRA cap had less moisture than the other three ($P = 0.004$ by one-way ANOVA; means shown in Table 4). This undoubtedly reflects the fact that the RCRA subplots only had 1 m of soil in which to store moisture, while the others had 2 m. There was sufficient plant cover to extract most of the plant-available water on the RCRA subplots, but not on the soil-only and biobarrier subplots. In contrast to native-vegetation subplots, crested-wheatgrass subplots receiving fall/spring irrigation had significantly higher end-of-season soil moisture means than did subplots receiving ambient precipitation during every year of the study (Table 6).

3.7 The Effects of Biobarriers on Soil Moisture Dynamics within the Soil Profile

The subsequent analyses consist of two-way ANOVA's used to compare soil moisture dynamics among different sections of the soil moisture profile. These analyses assess the impacts of disrupting the soil profile with a gravel/cobble biobarrier on soil moisture dynamics. In addition, we assess the interaction of biobarriers and vegetation type on soil moisture extraction.

Ambient Precipitation, Shallow Biobarrier. Under ambient precipitation, the top 0.5 m of soil above shallow biobarriers had significantly lower end-of-season moisture content than the top 0.5 m of soil in the soil only caps (Table 7A). The end-of-season soil moisture difference between cap types was significant in all years from 1995 through 2000. There was no significant difference in end-of-season soil moisture between vegetation types in the top 0.5 m of soil of the shallow biobarrier caps and the soil only caps.

No significant end-of-season soil moisture difference between cap type or vegetation type occurred in the bottom 1.5 m of soil below the shallow biobarrier caps and the bottom 1.5 m of soil in the soil only caps (Table 8A).

Ambient Precipitation, Deep Biobarrier. End-of-season soil moisture contents in the 1.0 m of soil above the biobarrier in the deep biobarrier caps, the top 1.0 m of soil in the soil only caps, and the 1.0 m of soil above the FML in the RCRA caps were significantly different in 1995, 1996, 1997 and 2000 (Table 9A). In 1995 and 2000, end-of-season soil moisture was lower in the 1.0 m of the deep biobarrier caps than in the top 1.0 m of the soil only caps and the soil above the flexible membrane liner in the RCRA caps. In 1996 and 1997, the soil above the deep biobarrier was significantly drier than the 1.0 m of soil in the RCRA caps. There were no significant differences between vegetation types in end-of-season moisture in the top 1.0 m of soil.

Under ambient precipitation, there were no significant differences between cap type or vegetation type in end-of-season soil moisture in the 1.0m of soil below the deep biobarrier and the bottom 1.0 m of soil in the soil only caps (Table 10A).

Summer Irrigation, Shallow Biobarrier. End-of-season soil moisture content was significantly lower in the 0.5 m of soil over the shallow biobarrier than in the top 0.5 m of soil in the soil only caps in 1996, 1998, 1999 and 2000. Cap-type differences were marginally significant in 1995 and 1997. There were no end-of-season soil moisture differences between vegetation types (Table 7B).

In 1995, the 1.5 m of soil below the shallow biobarrier had significantly higher end-of-season soil moisture than the bottom 1.5 m of soil in the soil only caps. Few plants likely rooted below the shallow biobarrier by 1995, because of the sudden drop in soil moisture availability in the gravel/cobble biobarrier. Plants in the continuous soil profile likely had rooted deeper in the profile in 1995. Augmented summer precipitation increased soil moisture below the biobarrier that was not as readily extracted as water in the corresponding section of the soil only caps, apparently because of differences in root densities.

End-of-season soil moisture was higher in the bottom 1.5 m of the shallow biobarrier and soil only caps planted to crested wheatgrass than it was in those sections of the soil profile for caps having native vegetation. Those differences were significant in 1997 and 1998 (Table 8B).

Summer Irrigation, Deep Biobarrier. Under summer irrigation, end-of-season soil moisture in the top meter of soil differed significantly among the soil only, deep biobarrier, and RCRA caps in 1995, 1996, and 1997. The top 1.0 m of soil in the deep biobarrier caps was significantly drier than the soil overlying the FML in the RCRA caps in 1995. In 1996 and 1997, end-of-season soil moisture content was significantly higher in the 1.0 m of soil of the RCRA caps than in the same profile sections of both the soil only and deep biobarrier caps (Table 9B).

Higher end-of-season soil moisture in RCRA caps, compared to the top 1.0 m of soil in soil-only and deep biobarrier caps, is difficult to explain. We would have expected plants to extract all available moisture from a 1-m deep soil. One possible explanation for the difference is that late season extraction of water may have been lower on RCRA caps because cover of shrubs that remain active late in the season was lower (see section 3.12).

Vegetation types differed significantly in end-of-season moisture in the top 1.0 m of soil for all three cap types from 1996 through 2000. In all years, caps having native vegetation averaged 3-5% lower end-of-season moisture than that of caps with crested wheatgrass.

There was no significant cap type or vegetation type difference in end-of-season soil moisture in the bottom 1.0 m of soil between the soil only and deep biobarrier caps (Table 10B). Summer irrigation resulted in a shallow wetting front that never extended to a depth of 1 m in the soil profile; therefore, the bottom 1.0 m of soil in the soil only and deep biobarrier caps was not affected by summer irrigation.

Fall/Spring Irrigation, Shallow Biobarrier. Under fall/spring irrigation, end-of-season soil moisture was significantly lower in the 0.5 m of soil above the shallow biobarrier than it was in the top 0.5 m of soil in the soil only caps in 1995 and 1997 through 2000. There were no significant differences in soil moisture in the top 0.5 m of soil between vegetation types (Table 7C).

From 1997 through 2000, end-of-season soil moisture in the bottom 1.5 m of the shallow biobarrier and soil only caps was significantly higher in shallow biobarrier caps (Table 8C). This difference indicates that plant roots were better able to extract water from deep in a continuous soil profile than from the bottom of a profile interrupted by a biobarrier. Vegetation types also differed significantly in end-of-season soil moisture in the bottom 1.5 m of soil from 1997 through 2000 (Table 8C). In all years, caps planted in crested wheatgrass had higher end-of-season soil moisture in the bottom 1.5 m of the profile than native-vegetation caps.

Significant interactions between cap type and vegetation type occurred in 1997, 1999, and 2000 (Table 8C). Results from Tukey's tests indicate that the bottom 1.5 m of soil below shallow biobarriers planted with crested wheatgrass had the highest end-of-season soil moisture content, while the soil-only caps with native vegetation had the lowest. Thus, under fall/spring irrigation, the reduced ability of plants to extract water from below a biobarrier was compounded by lower water use of crested wheatgrass because of its low cover (see 3.10).

Fall/Spring Irrigation, Deep Biobarrier. Under fall/spring irrigation, end-of-season soil moisture content in the top 1.0 m of the soil only caps, the deep biobarrier caps, and the RCRA caps differed significantly only in 1997, when end-of-season soil moisture was significantly lower in the 1.0 m of soil above the deep biobarrier than in the 1.0 m of soil above the FML on the RCRA caps (Table 9C). Vegetation significantly affected end-of-season soil moisture in the top 1.0 m of soil in 1999 following the irrigation to breakthrough trials. Caps planted in crested wheatgrass had significantly higher moisture than native-vegetation caps (Table 9C).

End-of-season soil moisture in the bottom 1.0 m of the deep biobarrier and soil-only caps was significantly higher in deep biobarrier caps in 1997 (Table 10C). A significant interaction indicates that higher end-of-season soil moisture in deep biobarrier caps planted in crested wheatgrass caused the significant difference. Vegetation type caused significant differences in end-of-season soil moisture content in the bottom 1.0 m of soil in 1997 through 2000. As with the portion of the soil profile below the shallow biobarrier caps, native vegetation appears better able than crested wheatgrass to extract water from deep in the soil profile of deep biobarrier caps under fall/spring irrigation.

3.8 Irrigation to Breakthrough Trials, 1999

Irrigation to breakthrough trials were conducted in April and May of 1999 on all fall/spring subplots. Representative moisture profiles are shown in the 1999 frames of Figures 29 – 32. There was no significant difference among the soil-only and biobarrier caps or between vegetation types in the amount of water required to cause drainage. Means ranged from 607 to 727 mm (Table 11A); these estimates include water in the profile when the trials began plus the amount of irrigation and precipitation received. These values are surprisingly high, but because plants were transpiring and the soil surface was continually wet during the 32 days over which the trials were conducted, ET would have removed a substantial amount of that water. A conservative ET estimate of 5 mm/day over the period would account for 160 mm of water. Furthermore, some of the water in the profile at breakthrough ultimately would have drained from the plots.

Estimates of the amount of water in the profile at breakthrough were very similar among the soil-only and biobarrier caps, with an overall mean of 607 mm (Table 11B). These values are consistent with an estimated field capacity of 28%, which would translate to 560 mm of water in a 2-m depth of soil.

3.9 Post Irrigation to Breakthrough Soil-Moisture Dynamics

To examine recovery of moisture storage capacity after irrigation to breakthrough, we compared end-of-season water content for each cap-type/vegetation combination for 1998 (pre-irrigation to breakthrough), 1999, and 2000. For subplots having native vegetation, average moisture content in the total soil profile was reduced to 16% or less by the end of the 1999 season and were not significantly different from the 1998 values, except for the RCRA subplots which were drier in 1999 than in 1998 (Table 12). Furthermore, mean values were very similar among cap types, indicating that emplacement of a biobarrier did not significantly affect the effective storage capacity of a cap. Analyses of different portions of the soil profile revealed only one case where mean water content was significantly higher ($P < 0.05$) at the end of the 1999 growing season than it had been in 1998: Mean water content in the bottom 1.0 m of soil on the deep biobarrier subplots was 18.3% in the fall of 1999 vs. 16.9% in 1998. Thus, with native vegetation, most caps had fully recovered their capacity to store water by the end of the same season in which that storage reservoir had been completely full. Means were generally lower after the 2000 growing season, which was exceptionally dry (Table 12).

Results were generally similar for the crested-wheatgrass subplots, except that the end-of-season water contents for all but the RCRA subplots were considerably higher in all three years than on the native-vegetation subplots (Table 12). However, on the deep biobarrier subplot, water content in 1999 was significantly higher than in either 1998 or 2000. Thus, for that cap type, 2 years were required to reset the storage reservoir. Further comparisons of the two vegetation types are given in the next section.

3.10 Differences in Performance of the Two Vegetation Types

Plant cover on the plots planted to crested wheatgrass developed very rapidly during 1994 and 1995. By the end of the 1995 growing season, cover on the crested-wheatgrass subplots averaged 43%, double that on the native-vegetation subplots (Tables 2, 3). The cover on the crested-wheatgrass subplots was considerably higher than that measured on four areas at the INEEL seeded to crested wheatgrass in the 1950's and 1960. Cover was remarkably similar in those four stands, which were essentially crested wheatgrass monocultures, ranging from 34% to 36% (Anderson and Marlette 1986). Beginning during the winter of 1995-96, there was substantial lodging of dead tillers and production of litter on the PCBE crested-wheatgrass subplots, sharply reducing cover. Cover was not measured on those plots again until 2000 at which time it averaged about 50% of that in 1995; it was lower in 2000 than in 1995 for all cap types and under all precipitation/irrigation regimes (Table 3). In 2000, cover on crested-wheatgrass subplots differed little among cap types or precipitation/irrigation treatments (Table 3, Figure 38), whereas native-vegetation subplots maintained higher cover under both summer and fall/spring irrigation than under ambient precipitation (Figure 38). Furthermore, native-vegetation subplots had higher cover than crested-wheatgrass subplots under all precipitation/irrigation regimes and on all cap types in 2000 (Figure 38, Table 13).

The consequences of reduced cover on the crested-wheatgrass subplots were evident as early as 1996, when significantly more water remained in the soil at the end of the growing season on subplots receiving supplemental irrigation (both summer and fall/spring) than on those that received only ambient precipitation (Table 6). Similar, highly significant differences were observed in each subsequent year of the study (Table 6). These trends are readily apparent as a steady year-to-year increase in water remaining in the soil of biobarrier subplots planted to crested wheatgrass and receiving fall/spring irrigation (Figure 7C). Subplots with native vegetation do not show a similar trend (Figure 7C). It should be noted that there was a substantial decrease in perennial grass cover on native-vegetation subplots in 1997 (Figure 8), but increases in shrub cover offset those losses, so there was sufficient plant cover on the native-vegetation subplots to use all of the moisture available.

We used *t* tests to compare end-of-season soil moisture between crested-wheatgrass and native-vegetation subplots for each cap type under the three precipitation/irrigation regimes in 1998, a year in which the total amount of distribution of precipitation were close to long-term averages. There was no significant difference between means under ambient precipitation; in fact, all means were within 1.5% (Table 14). In contrast, under summer irrigation, the RCRA and deep biobarrier caps with crested wheatgrass had significantly more end-of-season moisture than those having native vegetation, and the difference for the shallow biobarrier subplots was marginally significant (Table 14). Under fall spring irrigation, moisture was significantly higher on the shallow and deep biobarrier caps with crested wheatgrass than with native vegetation (Table 14). It is noteworthy that, although differences were not always significant (probably due to small samples sizes), all means for crested wheatgrass were higher than those for native subplots under irrigation treatments (Table 14).

3.11 Extraction of Soil Moisture below Biobarriers – Results of Soil Coring and Lithium Tracer Studies

As mentioned previously, decreases in soil moisture content below biobarriers indicated extraction by plant roots rather than drainage due to unsaturated flow (see section 3.6, Deep Biobarrier Cap). Nevertheless, we sought definitive evidence that roots were present and extracting moisture below biobarriers. Live roots were present in all soil core samples taken in the fall of 1998. Mean root weights were not significantly different between shallow or deep biobarrier samples and similar depths in soil-only subplots.

Lithium content of plants near soil core tubes confirmed the presence of roots. Crested wheatgrass on shallow biobarrier plots had significantly higher lithium content in individuals adjacent to tubes than in those remote from tubes (Table 15). We did not have enough replicates of any of the other species/biobarrier combination to test differences statistically, but for every pair of individuals samples, except one pair of gray rabbitbrush (*Chrysothamnus nauseosus)* samples, tissue from the individual adjacent to the lithium tube always contained a higher concentration of lithium than did the paired remote individual. In many cases, lithium content in the individual adjacent to the lithium tube was one to several orders of magnitude higher than that of the paired individual (Table 15). These data show that individuals representing numerous species and all growth forms were able to bridge a 0.5-m thick gravel/cobble biobarrier with their root system and extract water from below the biobarrier.

3.12 Effects of Cap Type and Irrigation Treatment on Composition of Native Vegetation

Cap configuration interacted with irrigation treatment to produce interesting and important differences in the structure of native vegetation. In 1993, all native-vegetation subplots were planted in equal densities of shrubs and grasses. Dead plants were replaced in 1994 to maintain those densities. By 1997, there was a significant difference in shrub cover among cap types ($P = 0.055$), resulting from higher cover of gray rabbitbrush on shallow biobarrier plots. This trend continued, and by 2000, mean cover of gray rabbitbrush was higher on shallow biobarrier plots of all three precipitation/irrigation treatments, but especially on the subplots receiving fall/spring irrigation (Figure 39). These results indicate strong selection for this deep-rooted shrub on shallow biobarrier caps and suggest that this species may be better able than other species on the plots to bridge a biobarrier with its root system. Water frequently percolates below the shallow biobarriers, especially under fall/spring irrigation, providing a reservoir of moisture that may be more readily available to gray rabbitbrush than to competing species.

The interaction between irrigation treatment and cap configuration also influenced the cover of sagebrush. Under ambient precipitation, sagebrush cover increased modestly over the six years on all caps and was very similar among caps in 2000 (Figure 39). Either increased summer or spring/fall irrigation tended to increase sagebrush cover on shallow biobarrier plots, while fall/spring irrigation resulted in a large increase in sagebrush cover on deep biobarrier subplots and a dramatic decrease on RCRA subplots (Figure 39). We expected that deep moisture storage would favor sagebrush, but we were surprised by the strong selection against it on RCRA subplots receiving spring/fall irrigation. Sagebrush is known to be intolerant of anaerobic soils (Lunt et al. 1973). We suspect that the fall/spring irrigation treatment on RCRA plots occasionally results in sufficiently low oxygen levels to kill sagebrush plants.

There were numerous significant interactions between cap configuration and precipitation/irrigation treatment in the cover of perennial grasses (Morris 2001). Rhizomatous grasses tended to be favored on RCRA subplots receiving summer irrigation and on deep biobarrier subplots receiving fall/spring irrigation. Timing of water availability appeared to have a larger effect on perennial grasses than on shrubs; a sharp increase in perennial grass cover was apparent in 2000 in response to fall/spring irrigation.

4.0 Discussion

4.1 Differential Performance of the Four Cap Configurations under Ambient and Augmented Precipitation (Objectives 1 and 3).

Under ambient precipitation and summer irrigation, all of the cap types performed satisfactorily and quite similarly. Given the similar climatic conditions that have prevailed on the upper Snake River Plain for the last10,000 years (Davis 1981, Davis et al. 1986, Beiswenger 1991), a landfill cap constructed according to any of the cap configurations included in this study likely would prevent water received as precipitation from reaching interred wastes, so long as the caps supported a healthy community of drought-tolerant perennial plants. This, of course, assumes no drainage of water onto the cap and no subsidence that would cause pooling of water following snowmelt. We have demonstrated that even a very large increase in summer precipitation would not adversely impact cap performance. With increased winter precipitation (fall/spring irrigation treatment), differences in cap performance became more important, but the soil-only and biobarrier caps were still capable of storing and returning to the atmosphere far more moisture than the precipitation expected under current climate change scenarios. Thus, the soil-only and biobarrier caps should preclude water from reaching buried wastes, even with a considerable increase in winter precipitation. Nevertheless, there are important differences that translate to advantages or disadvantages of the various configurations.

Soil-only Cap. This study confirms the conclusions of earlier studies at the INEEL (Anderson et al. 1991, 1993) that a cap consisting of a 2-m depth of soil would prevent percolation of water into interred wastes. This depth of soil is more than adequate to store the water received as precipitation under present or predicted future climates, so long as healthy perennial vegetation is present to empty that storage reservoir each year. Our results indicate that the soil wetting front would rarely reach the bottom of a 2-m soil cap. Hence, once plants extracted the available water from the entire soil profile, we would expect hydraulic conductivity of the dry soil at the bottom of the cap to remain very low, perhaps 10^{-10} to 10^{-12} cm/s (see section 3.3). Furthermore, because root activity would be limited to those soil depths having plant-available water, we would not expect roots to grow beyond the depth of the wetting front each year. Thus, root intrusion into buried wastes should not be a problem once the vegetation initially dries the soil cap.

A 2-m cap of soil should provide sufficient depth to accommodate the maximum observed burrowing depths of small mammals (Reynolds and Wakkinen 1987, Reynolds and Laundre 1988, Laundre 1989, Laundre and Reynolds 1993, Pratt 2000) and harvester ants (Blom 1990, Gaglio et al. 1998). Laundre (1993) demonstrated that small mammal burrows increased water percolation into soils at the INEEL by very modest amounts. Small mammals have been abundant on the PCBE since its inception; we have seen no evidence that their activities adversely affected cap performance. Gaglio et al. (1998) found that harvester ant nests increased percolation rates on PCBE soils, but those soils dried faster than undisturbed soils. They concluded that nests of harvester ants "do not pose an immediate threat to the ground water under low level nuclear waste buried under a 2-m protective cap." Given these observations and results, we conclude that native animal threats to the integrity of a 2-m soil cap are minor.

Shallow Biobarrier Cap. Shallow biobarrier caps generally performed as well as the other cap configurations. We found that roots of numerous species can bridge a 0.5-m thick biobarrier and extract water from the underlying soil, so indeed it is possible to have a portion of the storage reservoir below a biobarrier. However, this design has numerous disadvantages that make it the least favorable alternative to a RCRA cap. The results show that 0.5 m of soil above a biobarrier is insufficient to store the precipitation received in most years, so water will routinely percolate into the soil below, providing a reservoir of deep soil moisture. Placement of the biobarrier at a shallow depth caused strong selection for gray rabbitbrush, a native shrub known to rely primarily on deep moisture reserves. Encouraging the growth of this deeply rooting species could result in intrusion of roots into buried wastes if any water was available in the waste zone.

Although we have good evidence that animals will not burrow through a biobarrier having a meter of overlying soil, we do not have definitive evidence that a 0.5-m thick biobarrier is sufficient to preclude burrowing if the overlying soil is considerably thinner (Pratt 2000). Hence, another potential disadvantage of shallow biobarrier placement is that it would not provide sufficient burrowing depth to meet the needs of small mammals or ants, which, in turn, might encourage those species to burrow into and possibly through the biobarrier.

Deep Biobarrier Cap. Under ambient precipitation and summer irrigation, we seldom saw any change in water content below deep biobarriers; water typically did not percolate below the biobarriers during spring recharge, and there was no extraction of water from the soil below the biobarriers. The stability of the moisture profiles below biobarriers over a growing season (e.g., Figures 12, 17) reflects the very low hydraulic conductivity of these relatively dry soils. Under winter precipitation, water occasionally percolated below the biobarriers (e.g., Figure 31), but in many cases heavy irrigation in the fall coupled with ambient precipitation during the winter and spring did not result in any increase in water content below biobarriers (e.g., Figure 35). Given these results, a deep-biobarrier configuration is one of the caps recommended for isolating hazardous wastes at the INEEL (see below).

RCRA Cap. The minimum soil depth recommended for a RCRA cap is 0.6 m (USEPA 1989). We found that 1 m of soil overlying an impervious FML was inadequate to store the precipitation received during 1995, an exceptionally wet year. Under fall/spring irrigation, there typically was little if any reserve storage capacity at the beginning of the growing season and drainage off the FML was sometimes observed. Thus, the main disadvantage of the RCRA-recommended cap is that provision would have to be made for disposing of water that would occasionally drain off the cap over the FML. This would substantially increase construction complexity and cost. Furthermore, it is possible that water so disposed of could run back under the cap, depending on the configuration of underlying substrata. We argue that, at sites such as the INEEL where potential evapotranspiration is so much higher than precipitation, it makes much more sense to design caps so that no provision for drainage is necessary.

Another concern with the RCRA cap is life of the FML. Research elsewhere has shown that, should an FML becomes damaged, we would expect plant roots to quickly extract water from the underlying compacted clay layer, resulting in it drying, cracking, and subsequently allowing deep water percolation (Daniel and Gross 1995). Thus, the long-term integrity of a RCRA cap in arid and semiarid environments is questionable (Suter et al. 1993).

A RCRA cap would also be more expensive and difficult to construct than a soil-only or biobarrier cap. Soil with sufficient clay content to form the compacted clay layer usually has to be imported at considerable cost. That soil is difficult to work with. Great care must be taken to seal overlapping sheets of FML and to prevent damage to the FML as overlying soil is emplaced.

The only potential advantage that we see for a RCRA cap is that the FML might prevent drainage into wastes in the event of cap subsidence that caused local pooling of water, assuming that the FML remained intact. Given concerns about long-term integrity of a FML and the increased complexity and cost compared to the alternative configuration that we evaluated, we cannot recommend the RCRA cap for the INEEL or similar semiarid environments.

4.2 Effects of Biological Intrusion Barriers on Soil Moisture Storage and Extraction (Objective 2).

The gravel/cobble biobarriers in this study interrupted the soil water-storage reservoir at depths of either 0.5 m or 1 m. The results demonstrate that it is feasible to place a biobarrier within a soil profile, i.e., to have a portion of the storage reservoir below a biobarrier. Roots of several species bridged biobarriers (Table 15), and the results show definitively that plants will extract water from all depths of soil below biobarriers (Figure 28). Indeed, on shallow biobarrier plots, roots proliferated in and extracted water from a 1.5-m depth of soil below biobarriers.

Because of the capillary break between the fine textured soil and the gravel at the top of the biobarrier, water content of the soil above the biobarrier must approach saturation before water will percolate through it (Sackschewsky et al. 1995, Hillel 1998, Porro 2001). This effect maximizes the amount of water stored in the overlying soil, as clearly shown in Figure 35 (see Porro 2001 for complementary data from INEEL). Consequently, 1 m of soil was often sufficient to store fall/spring irrigation plus ambient precipitation.

Results from deep-biobarrier caps indicate there may be a threshold water content below which plants are unable to detect the presence of water below a 0.5-m thick biobarrier. Plants extracted water from soil below deep biobarriers (e.g., Figures 28, 31), but only when water content of the soil immediately below the barrier was at least 25% by volume.

Several trends in soil-moisture dynamics emerge from our analyses of the effects of biobarriers. First, under fall/spring irrigation, end-of-season soil moisture was typically higher below shallow biobarriers than at similar depths in soil-only caps. These results indicate that plants extracted water more effectively from a continuous soil profile than from one interrupted by a biobarrier. Second, end-of-season soil moisture in soil overlying a gravel/cobble biobarrier tended to be lower than that of comparable depths in a continuous soil profile. This trend was especially apparent on shallow biobarrier caps. This difference probably reflects the combined effects of more thorough extraction of water by plants in the soil above a biobarrier coupled with evaporation from a profile where depth is limited by a capillary break (see Porro 2001). Finally, caps with native vegetation tend to have lower end-of-season soil moisture than caps with crested wheatgrass both above and below biobarriers, particularly in caps receiving augmented precipitation. Differences in end-of-season soil moisture of even 3-5% affects the storage capacity of a cap, and could make the difference between a cap functioning effectively or failing during a series of wet years. Reasons for differences between the vegetation types are discussed in the next section.

In summary, we found no advantage of placing a biobarrier at a shallow depth in an ET cap. However, placing a gravel/cobble biobarrier at the bottom of an ET cap will take advantage of the capillary break at the soil/gravel interface and maximize the storage capacity of the overlying soil.

4.3 Differential Performance of Vegetation Types (Objective 4).

For reasons given in the introduction, we predicted that an analogue to a natural sagebrush-perennial grass community would perform better and require less maintenance than a perennial grass monoculture. The results support this prediction. Using a combination of transplanting and seeding, we readily established diverse communities on the experimental plots. Shrubs, perennial grasses, and perennial forbs all grew vigorously. All species planted became established, although over time some species became locally extinct on some subplots. Twelve species were originally planted; by 2000, some 27 species were recorded on the native-vegetation subplots. We expect such artificial communities to be dynamic, to vary in total plant cover and species composition through time just as natural sagebrush communities do (Anderson and Inouye 2001).

As expected, crested wheatgrass established quickly and grew vigorously on the subplots where it was planted, just as it had in our earlier study (Anderson et al. 1987). However, after supplemental irrigation to facilitate establishment and a very wet growing season in 1995, the stands of crested wheatgrass were so dense that they became self inhibiting. Live cover on those plots subsequently decreased by about 50%, and, on plots receiving supplemental irrigation, not all of the plant available water in the caps was withdrawn each year. The result was less capacity to store moisture received prior to the next growing season. Higher end-of-season water content on crested-wheatgrass subplots was likely attributable to both lower cover and the absence of shrubs. Shrubs such as sagebrush and the rabbitbrushes remain active late in the growing season, continuing to extract soil moisture after many grasses and forbs are senescent.

Although grass cover also decreased following a peak in 1997 on the native-vegetation subplots, shrub cover increased (Figure 9). As a consequence, the native vegetation typically used all of the water available in the soil cap each year, maintaining a constant size of reservoir available to store precipitation.

Not only did the native species maintain high cover and use all of the water available under supplemental irrigation, they also demonstrated a remarkable capacity to adjust cover to the amount of water available (Figure 38). In 2000, cover was higher on the summer irrigation subplots than on those receiving only ambient precipitation, and, with the exception of the RCRA-cap subplots, cover was higher on the fall/spring irrigation subplots than on the summer irrigation subplots (Figure 38). The data for the native subplots receiving fall/spring irrigation are particularly instructive. Cover was higher on the soil-only and biobarrier subplots than on the RCRA subplots (Figure 38). This reflects the fact that the RCRA subplots have but 1 m of soil in which to store the additional water, whereas the other caps have 2 m of soil for storage. The native vegetation was capable of responding to the additional water-availability. No such trend is apparent on the crested-wheatgrass subplots (Figure 38).

4.4 Recommendations for Waste Cap Configurations at the INEEL

Based on the results of the PCBE and the considerations discussed above, we recommend two cap configurations: a soil-only cap consisting of a 2-m depth of homogeneous soil or a cap consisting of a 1.2-m depth of homogeneous soil overlying a 0.5-m thick gravel/cobble intrusion barrier. Caps constructed according to either of these configurations should preclude virtually any precipitation water from reaching interred wastes.

A major advantage of a soil-only cap is simplicity of construction. A disadvantage is the relatively large amount of soil required. Construction cost will depend largely on availability of soil and the distance it must be transported. If fill soil is limited and if gravel and cobble (or similar materials, see Reynolds 1990) are readily available, then a cap incorporating a biobarrier and requiring less soil might be a better choice.

Although 1 m of soil above a biobarrier was generally adequate to store precipitation received, during 1995, the wettest year on record at the INEEL, water percolated below the biobarrier on two of 18 deep-biobarrier subplots. Therefore, we recommend a minimum of 1.2 m of soil overlying a biobarrier. A cap consisting of 1.2 m of soil overlying the capillary break of the biobarrier should be more than adequate to store precipitation received during exceptionally wet years. Furthermore, this configuration should prevent intrusion by burrowing animals, and it should restrict root growth so long as the underlying materials are relatively dry.

Cap Construction and Surface Topography. The PCBE results demonstrate that and ET cap configured according to the recommendations above should prevent water from reaching buried wastes. Constructing the cap level and on grade with surrounding terrain eliminates any provision for drainage off cap layers, eliminates side slope problems, and reduces the potential for wind or water erosion. Thus, for a new burial site, we recommend this overall configuration. Each component of a cap should be horizontal. Soil should be emplaced in small, horizontal lifts (0.1 to 0.2 m) to avoid creating pitched layers that might provide pathways for preferential flow. Soils should be uniformly compacted to avoid subsequent subsidence that could cause pooling of water on the surface. The cap should be configured to minimize the potential for water to drain onto it from surrounding terrain.

For ET caps constructed to cover existing landfills or contaminated soil, it may be necessary to construct the entire cap above grade. In such a case, it may be desirable to configure the cap with a slight slope on the surface, which could prevent pooling of water on the surface following snowmelt or heavy precipitation. If the surface is sloped, it should be a very shallow slope (e.g., 2%) so that runoff from the cap is minimal (i.e., except for unusual circumstances, all of the precipitation received infiltrates the soil. This will ensure that sufficient moisture will be stored to maintain good vegetative cover.

For any cap constructed over an existing landfill or contaminated soil, we recommend placing a biobarrier on top of the existing cover or soil. This will help ensure that no moisture moves into the contaminated materials. The new cap should be constructed late in the growing season when the soil of the existing landfill or contaminated area is dry. This will reduce the likelihood of roots growing from the new cap into the contaminated zone.

4.5 Recommendations for Waste Cap Vegetation at the INEEL

Despite theoretical models that may indicate to the contrary (e.g., UNSAT-H, Fayer and Jones 1990), empirical evidence from previous studies (e.g. Anderson et al. 1987, 1993) and the present experiment demonstrate without question that the bulk of water lost from an ET cap during the growing season is extracted and transpired by plants. For a cap to function effectively and consistently, a healthy stand of perennial, drought adapted plants is essential. The objective is to establish a plant community that will be self-maintaining.

Anderson et al. (1987) showed that dominant native and introduced species at the INEEL differed little in their seasonal patterns of water use or in the extent to which they could dry a soil. Thus, other ecological characteristics, such as persistence in a stand, ease of establishment, tolerance to pests, ability to resprout or re-colonize following disturbances such as fire, and potential for self-inhibition due to accumulations of standing dead materials and litter, are probably more important considerations in choosing species for cap vegetation. Species recommended for ET caps at the INEEL are shown in Table 16. These species all occur naturally at the INEEL, although commercially available cultivars have been developed from genetic stock derived elsewhere.

Because it is crucial to get vegetation established on ET caps as quickly as possible, it is best not to rely entirely on establishment from seed. The success of seeding varies greatly from year to year, depending on amounts and timing of precipitation. Therefore, we recommend transplanting shrubs and some of the perennial grasses. Although we have found that "wildings" transplanted from local communities survive well (Shumar and Anderson 1987), this technique is labor intensive and, because of impacts on the local vegetation, is only feasible for small revegetation projects. An alternative is to contract with a private firm to collect seed from desired species at the INEEL, grow seedlings in plastic tubes in a greenhouse, and then plant that "container stock" on the ET cap. Transplanting container stock can be combined with drill seeding of grasses and forbs known to establish well from seed, such as wheatgrasses and several forbs. Current cost for collecting seed, growing container stock, and planting the seedlings is about $1.00 per seedling.

The planting density used in the PCBE resulted in excellent vegetative cover. Therefore, we recommend that seedlings be planted into a grid spacing of approximately 0.75 m and in a pattern so that conspecifics are not adjacent to one another. One approach would be plant seeded species first with a conventional agricultural drill in which every other, or perhaps two out of three, drop tube(s) are blocked to increase the spacing between rows. Then, container stock could be planted at 0.75 m intervals between drill rows. Seeding and transplanting can be done either in fall (late October or early November) or early spring (April). A gravel mulch applied to the surface of the cap can retard evaporation, enhance seedling establishment, and reduce erosion (Winkel et al. 1991, Waugh et al. 1994, Sackschewsky et al. 1995). Gravel was applied to the surface of the PCBE plots to achieve about 75% surface cover.

If possible, arrangements should be made to provide some supplemental irrigation during the first growing season. This will help to ensure development of a vigorous stand of plants. Periodic irrigation (e.g., every other week from mid May through June) should suffice, depending on amounts of natural precipitation received. Sufficient water should be applied to drive the wetting front to a depth of 0.25 to 0.3 m each time. There is no need for concern about this irrigation causing cap breakthrough. Once plants are established, they will quickly use the supplemental water.

Monitoring and Maintenance of an ET Cap. As stated earlier, the objective is to establish permanent vegetation and natural ecosystem processes on ET caps that will function over the long term with minimal maintenance. We are confident that this objective can be met by developing an analogue of a natural plant community on the caps. However, care must be taken to ensure that good vegetative cover develops and that the surface of the cap remains free from depressions that could cause pooling of water and its subsequent drainage into the waste zone. During the first year or so, vegetation development should be closely monitored. If seedings fail, it may be necessary to repeat drilling of seed. Transplants that die should be replaced. Any sizeable depressions should be repaired and re-planted. Over the long-term, periodic monitoring to ensure that the surface remains free of depressions and well vegetated should be all that is necessary.

4.6 Meeting Equivalency Criteria

Demonstrating that the performance of an ET cap will be equivalent to an USEPA-prescribed cap may be required for approval of the ET cap by regulatory agencies. Equivalency criteria are usually site specific and are based on an assumed percolation rate for an EPA prescribed cover (Benson et al. 2001). Because we did not measure percolation from the bottom of experimental caps directly, and because we used the water balance equation assuming no drainage to estimate ET, our water balance and ET estimates cannot be used to demonstrate equivalency. In general, water balance methods are inadequate for demonstrating equivalency, even when ET is estimated from micrometeorological data (Benson et al. 2001). An alternative approach is to estimate percolation rates using Darcy's Law. Benson et al. (2001) indicate that this approach has a precision of one to two orders of magnitude and suggest that it can be used to demonstrate equivalency if the estimated percolation rate is at least two orders of magnitude lower than the equivalency criterion. We have estimated that the hydraulic conductivity of the PCBE soils at the lower limit of extraction by plants was very low, from 2×10^{-12} to 3×10^{-11} cm/s (see section 3.3). Thus, percolation rates from our recommended ET caps should be several orders of magnitude below that prescribed for caps at the INEEL, assuming that water content at the bottom of the cap remains near the lower limit of extraction. The cap configurations that we have recommended should satisfy that assumption.

4.7 Potential Threats to Integrity of ET Caps at the INEEL

Wildfire. Concern is often expressed about the potential for wildfire to remove the vegetative cover from an ET cap, which subsequently could cause the cap to fail. The risk of wildfire is greatest late in the growing season when soil moisture has been depleted and many perennial grasses and forbs will have become dormant. Research at the INEEL and elsewhere in the region has shown that most of the perennial grasses and many shrubs and perennial forbs can resprout following fire (e.g., Ratzlaff and Anderson 1994, Patrick and Anderson 1999). Vegetative cover of INEEL areas burned in recent wildfires has recovered quickly (Patrick and Anderson 1999). Thus, if vegetation on an ET cap includes a diverse mix of species and life forms, including healthy populations of perennial grasses, cover on the cap can be expected to recover to prefire levels within two growing season (S. Buckwalter and J. Anderson, unpublished data). It is likely that there would be sufficient cover in the first postfire season to use most of the precipitation received, but additional research is recommended to confirm this.

Invasive Annual Plants. Associated with the concern about wildfire is concern that postfire vegetation on an ET may become dominated by invasive annual species such as cheatgrass (*Bromus tectorum*). Research indicates that cheatgrass may not use all of the plant-available water in a deep soil (Cline et al. 1977, Anderson and Ratzlaff 1996). Accumulation of water might ultimately cause breakthrough of the cap. Postfire research at the INEEL and vicinity has shown that if vigorous populations of native perennial species are present when a wildfire occurs, the native community can recover and resist invasion by exotics (Ratzlaff and Anderson 1994, Patrick and Anderson 1999). Furthermore, cheatgrass does not establish well on fine-textured, clayey soils (Rasmuson 1996). On native-vegetation plots adjacent to the PCBE that were subjected to the same irrigation treatments as the PCBE plots, cheatgrass cover increased substantially in response to fall/spring irrigation (Morris 2001). However, on the PCBE plots, cheatgrass was rare and we observed no tendency for it to increase in response to irrigation. We conclude that if fine-textured soils are used for ET caps at the INEEL and climatically similar sites and that if those caps support a diverse community of native species, the risk of cheatgrass invasion is low.

Another invasive annual that may be problematic on disturbed sites having fine-textured soils is Russian thistle (*Salsola kali*). Russian thistle is very common at the INEEL and was abundant on PCBE plots and surrounding disturbed areas for the first few years after plots were established. Because of its photosynthetic pathway (C_4), it requires relatively little water and therefore is not a desirable component of vegetation on an ET cap. Our experience at the PCBE site is that Russian thistle will persist only until perennial species become well established. Hence, if care is taken to ensure development of a diverse community of perennials on an ET cap, Russian thistle and other annuals should not pose a serious problem.

Burrowing Animals. As noted earlier, ET caps constructed according to our recommendations should provide sufficient depth of soil to meet the habitat needs of burrowing small mammals and ants. Although small mammal burrows and ant nests may increase infiltration and percolation of water, such increases are very modest and should not pose a problem on vegetated caps (Laundre 1993, Gaglio et al. 1998). We did not investigate the potential impacts of badgers (*Taxidea taxus*) on cap performance, but they would not be expected to burrow deeper than do ground squirrels (*Spermophilus* sp.), their major prey. Research at the Hanford site in eastern Washington indicated that, although badger burrows increased infiltration of rainfall, vegetation quickly removed the excess moisture. In fact, soils were consistently dryer beneath burrows than in non burrow areas (Cadwell et al. 1989, Link et al 1995).

4.8 Conclusion

We conclude that an ET cap constructed according to the recommendations above will preclude precipitation water from reaching interred wastes at the INEEL and climatically similar sites. The recommended cap configurations provide a low cost, low maintenance alternative to EPA's recommended RCRA cap and to more complex , highly engineered designs. Over the past decade, increased interest in ET caps has resulted in a network of demonstration projects under the auspices of the Alternative Cap Assessment Project (ACAP), sponsored by the U.S. Environmental Protection Agency as part of the National Risk Management Research Laboratory's Superfund Innovative Technology Evaluation Program. ACAP currently is assessing performance of ET caps at 12 sites representing a variety of climatic regimes (for details, see http://www.dri.edu/Projects/EPA/boston-brochure2.html). The PCBE is a valuable complement of ACAP. Continued treatment and monitoring of the PCBE would provide much needed information on long-term performance of ET caps. The PCBE also provides opportunities for additional research to assess risks to cap integrity, including wildfire and invasion by annual weeds. We strongly recommend that DOE provide funding to take full advantage in its investment in a unique research facility.

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Table 1. Growth form, common name, and scientific name of species planted onto the native vegetation subplots of the Protective Cap/Biobarrier experiment at the Idaho National Engineering and Environmental Laboratory.

Growth Form	Common Name	Scientific Name
Shrubs:		
	Basin big sagebrush	*Artemisia tridentata ssp. tridentata*
	Wyoming big sagebrush	*Artemisia tridentata ssp. wyomingensis*
	Gray rabbitbrush	*Chrysothamnus nauseosus*
	Green rabbitbrush	*Chrysothamnus viscidiflorus*
	Winterfat	*Krascheninnikovia lanata*
Perennial Grasses:		
	Bottlebrush squirreltail	*Elymus elymoides*
	Great Basin wildrye	*Leymus cinereus*
	Indian ricegrass	*Achnatherum hymenoides*
	Needle-and-thread grass	*Hesperostipa comata*
	Thick-spiked wheatgrass	*Elymus lanceolatus*
Perennial Forbs:		
	'Appar' blue flax	*Linum perenne*
	Northern sweetvetch	*Hedysarum boreale*

Table 2. Mean plant cover in the spring and fall of 1995 on soil-only, shallow-biobarrier, deep-biobarrier, and RCRA subplots planted with native vegetation in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory.

	Cover (%)	
	Spring	**Fall**
Soil Only	10	20
Shallow Biobarrier	10	21
Deep Biobarrier	13	23
RCRA	12	25

Table 3. Mean cover in 1995 and 2000 of crested wheatgrass on soil-only, shallow-biobarrier, deep-biobarrier, and RCRA subplots under ambient precipitation, summer irrigation, or fall/spring irrigation in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Cap-type means followed by different letters, or yearly means underscored by different letters, are significantly different at P = 0.05 based on results of Tukey's multiple comparisons tests following two-way ANOVA's. In ANOVA table, significant P values are in bold typeface.

	1995	2000	**Mean**	
Ambient Precipitation	Cover (%)			
Soil Only	48	21	**35**	**a**
Shallow Biobarrier	39	21	**30**	**a**
Deep Biobarrier	37	16	**26**	**a**
RCRA	41	19	**30**	**a**
Mean	**41**	**19**		
	a	**b**		
Summer Irrigation				
Soil Only	48	25	**36**	**a**
Shallow Biobarrier	31	17	**24**	**a**
Deep Biobarrier	45	19	**32**	**a**
RCRA	46	19	**33**	**a**
Mean	**43**	**20**		
	a	**b**		
Fall/Spring Irrigation				
Soil Only	42	27	**35**	**a**
Shallow Biobarrier	37	21	**29**	**a**
Deep Biobarrier	45	23	**34**	**a**
RCRA	57	18	**37**	**a**
Mean	**45**	**22**		
	a	**b**		

Two-Way ANOVA Results

Source of Variation	DF	SS	MS	F	P
Ambient					
Year	1	2861.48	2861.48	21.79	**<0.001**
Cap	3	209.06	69.69	0.53	0.67
Year x Cap	3	67.82	22.61	0.17	0.91
Summer					
Year	1	3036.60	3036.60	9.68	**0.007**
Cap	3	473.46	157.82	0.50	0.69
Year x Cap	3	138.30	46.10	0.15	0.93
Fall/Spring					
Year	1	3100.60	3100.60	17.23	**<0.001**
Cap	3	221.44	73.81	0.41	0.75
Year x Cap	3	533.35	177.78	0.99	0.42

Table 4. Mean end-of-season soil moisture content (%) in the entire soil profile for each cap-type/vegetation combination under (A) ambient precipitation, (B) summer irrigation, and (C) fall/spring irrigation in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Crested refers to crested-wheatgrass vegetation; native refers to native vegetation. Vegetation means followed by different letters, or cap-type means underscored by different letters, are significantly different at P = 0.05 based on results of Tukey's multiple comparisons tests following two-way ANOVA's. Results of two-way ANOVA's are shown for each irrigation treatment following the table of means. In ANOVA tables, significant P values are in bold typeface.

A. Ambient Precipitation

	Soil Only	Shallow Biobarrier	Deep Biobarrier	RCRA	**Mean**	
1995						
Crested	14.3	15.0	13.3	12.5	**13.8**	**a**
Native	14.3	13.6	14.1	13.8	**13.9**	**a**
Mean	**14.3**	**14.3**	**13.7**	**13.1**		
	a	**a**	**a**	**a**		
1996						
Crested	15.2	15.4	14.5	13.6	**14.7**	**a**
Native	15.5	15.0	15.1	14.7	**15.1**	**a**
Mean	**15.3**	**15.2**	**14.8**	**14.2**		
	a	**a**	**a**	**a**		
1997						
Crested	15.5	15.7	15.1	15.0	**15.3**	**a**
Native	15.6	15.3	15.4	15.8	**15.5**	**a**
Mean	**15.5**	**15.5**	**15.2**	**15.4**		
	a	**a**	**a**	**a**		
1998						
Crested	15.6	15.4	16.3	14.8	**15.5**	**a**
Native	15.8	14.9	15.3	15.6	**15.4**	**a**
Mean	**15.7**	**15.2**	**15.8**	**15.2**		
	a	**a**	**a**	**a**		
1999						
Crested	18.2	15.5	17.6	16.3	**16.9**	**a**
Native	16.3	14.4	15.4	14.4	**15.1**	**a**
Mean	**17.2**	**15.0**	**16.5**	**15.4**		
	a	**a**	**a**	**a**		
2000						
Crested	16.7	15.3	16.0	14.2	**15.5**	**a**
Native	15.3	14.6	14.9	15.1	**15.0**	**a**
Mean	**16.0**	**14.9**	**15.4**	**14.6**		
	a	**a**	**a**	**a**		

Table 4 (continued).

Ambient Precipitation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	3	5.583	1.861	1.744	0.198
Vegetation	1	0.170	0.170	0.159	0.695
Cap x Vegetation	3	6.449	2.150	2.014	0.153
1996					
Cap	3	5.000	1.667	1.063	0.392
Vegetation	1	0.917	0.917	0.585	0.456
Cap x Vegetation	3	1.849	0.616	0.393	0.760
1997					
Cap	3	0.301	0.100	0.046	0.986
Vegetation	1	0.140	0.140	0.064	0.804
Cap x Vegetation	3	1.068	0.356	0.163	0.920
1998					
Cap	3	1.856	0.619	0.278	0.840
Vegetation	1	0.0771	0.0771	0.035	0.855
Cap x Vegetation	3	2.720	0.907	0.407	0.750
1999					
Cap	3	19.43	6.476	1.291	0.311
Vegetation	1	18.90	18.90	3.770	0.070
Cap x Vegetation	3	0.986	0.329	0.066	0.977
2000					
Cap	3	6.982	2.327	1.539	0.243
Vegetation	1	1.967	1.967	1.301	0.271
Cap x Vegetation	3	4.836	1.612	1.066	0.391

Table 4 (continued).

B. Summer Irrigation

	Soil Only	Shallow Biobarrier	Deep Biobarrier	RCRA	**Mean**	
1995						
Crested	13.7	16.5	12.6	15.1	**14.5**	**a**
Native	13.4	13.8	13.5	14.3	**13.8**	**a**
Mean	**13.6**	**15.1**	**13.1**	**14.7**		
	a	**a**	**a**	**a**		
1996						
Crested	17.9	16.6	17.4	21.5	**18.3**	**a**
Native	16.1	16.6	16.1	17.9	**16.7**	**b**
Mean	**17.0**	**16.6**	**16.8**	**19.7**		
	ab	**a**	**ab**	**b**		
1997						
Crested	17.8	17.6	18.3	22.4	**19.0**	**a**
Native	16.1	16.1	15.8	16.4	**16.1**	**b**
Mean	**16.9**	**16.9**	**17.0**	**19.4**		
	a	**a**	**a**	**b**		
1998						
Crested	18.3	17.9	19.2	22.2	**19.4**	**a**
Native	16.2	16.1	16.2	16.3	**16.2**	**b**
Mean	**17.2**	**17.0**	**17.7**	**19.3**		
	a	**a**	**a**	**a**		
1999						
Crested	18.1	17.1	18.3	21.1	**18.6**	**a**
Native	15.8	16.2	14.7	15.6	**15.5**	**b**
Mean	**16.9**	**16.6**	**16.5**	**18.4**		
	a	**a**	**a**	**a**		
2000						
Crested	17.3	17.0	17.7	19.2	**17.8**	**a**
Native	15.5	15.8	15.4	16.6	**15.8**	**b**
Mean	**16.4**	**16.4**	**16.6**	**17.9**		
	a	**a**	**a**	**a**		

Table 4 (continued).

Summer Irrigation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	3	16.98	5.658	1.239	0.328
Vegetation	1	3.096	3.096	0.978	0.422
Cap x Vegetation	3	9.573	3.191	0.699	0.566
1996					
Cap	3	39.26	13.09	4.015	**0.026**
Vegetation	1	16.06	16.06	4.926	**0.041**
Cap x Vegetation	3	9.758	3.253	0.998	0.419
1997					
Cap	3	27.49	9.164	7.384	**0.003**
Vegetation	1	51.16	51.16	41.222	**<0.001**
Cap x Vegetation	3	19.47	6.490	5.230	**0.010**
1998					
Cap	3	18.67	6.222	2.992	0.062
Vegetation	1	61.25	61.25	29.455	**<0.001**
Cap x Vegetation	3	15.81	5.270	2.534	0.094
1999					
Cap	3	13.76	4.586	1.217	0.336
Vegetation	1	56.70	56.70	15.055	**0.001**
Cap x Vegetation	3	17.09	5.696	1.512	0.250
2000					
Cap	3	9.044	3.015	1.029	0.406
Vegetation	1	23.74	23.74	8.104	**0.012**
Cap x Vegetation	3	1.654	0.551	0.188	0.903

Table 4 (continued)

C. Fall/Spring Irrigation

	Soil Only	Shallow Biobarrier	Deep Biobarrier	RCRA	**Mean**	
1995						
Crested	23.0	22.3	23.8	20.6	**22.4**	**a**
Native	22.8	22.8	21.5	22.5	**22.4**	**a**
Mean	**22.9**	**22.6**	**22.7**	**21.6**		
	a	**a**	**a**	**a**		
1996						
Crested	15.8	20.8	21.2	15.9	**18.4**	**a**
Native	20.7	20.0	19.1	18.5	**19.6**	**a**
Mean	**18.2**	**20.4**	**20.2**	**17.2**		
	a	**a**	**a**	**a**		
1997						
Crested	15.8	20.8	17.3	17.6	**17.9**	**a**
Native	16.1	16.2	15.0	15.5	**15.7**	**b**
Mean	**16.0**	**18.5**	**16.1**	**16.6**		
	a	**a**	**a**	**a**		
1998						
Crested	18.2	20.6	17.7	17.1	**18.4**	**a**
Native	15.7	16.3	14.5	15.4	**15.5**	**b**
Mean	**16.9**	**18.5**	**16.1**	**16.2**		
	a	**a**	**a**	**a**		
1999						
Crested	21.5	23.6	22.1	16.1	**20.9**	**a**
Native	15.7	15.7	15.2	16.9	**15.9**	**b**
Mean	**18.6**	**19.6**	**18.6**	**16.5**		
	a	**a**	**a**	**a**		
2000						
Crested	17.8	22.3	18.0	15.5	**18.4**	**a**
Native	15.1	15.4	14.7	14.5	**14.9**	**b**
Mean	**16.4**	**18.8**	**16.3**	**15.0**		
	a	**b**	**a**	**a**		

Table 4 (continued).

Fall/Spring Irrigation, Two-Way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	3	6.335	2.112	0.549	0.656
Vegetation	1	0.0121	0.0121	0.003	0.956
Cap x Vegetation	3	14.58	4.860	1.264	0.320
1996					
Cap	3	43.56	14.52	0.492	0.693
Vegetation	1	7.993	7.993	0.271	0.610
Cap x Vegetation	3	46.11	15.37	0.521	0.674
1997					
Cap	3	24.04	8.012	2.490	0.097
Vegetation	1	28.45	28.45	8.843	**0.009**
Cap x Vegetation	3	18.26	6.087	1.892	0.172
1998					
Cap	3	21.14	7.045	2.280	0.119
Vegetation	1	51.16	51.16	16.553	**<0.001**
Cap x Vegetation	3	5.476	1.825	0.591	0.630
1999					
Cap	3	31.28	10.43	2.947	0.064
Vegetation	1	149.6	149.6	42.279	**<0.001**
Cap x Vegetation	3	70.05	23.35	6.601	**0.004**
2000					
Cap	3	46.85	15.62	9.008	**<0.001**
Vegetation	1	71.48	71.48	41.229	**<0.001**
Cap x Vegetation	3	27.74	9.248	5.334	**0.010**

Table 5. Estimates of mean evapotranspiration (mm) for each cap-type/vegetation combination under (A) ambient precipitation, (B) summer irrigation, and (C) fall/spring irrigation in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Crested refers to crested-wheatgrass vegetation; native refers to native vegetation. Vegetation means followed by different letters, or cap-type means underscored by different letters, are significantly different at P = 0.05 based on results of Tukey's multiple comparisons tests following two-way ANOVA's. Results of two-way ANOVA's are shown for each irrigation treatment following the table of means. In ANOVA tables, significant P values are in bold typeface.

A. Ambient Precipitation

	Soil Only	Shallow Biobarrier	Deep Biobarrier	RCRA	**Mean**	
1995						
Crested	355	342	349	329	**344**	**a**
Native	320	319	353	334	**332**	**a**
Mean	**338**	**331**	**351**	**331**		
	a	**a**	**a**	**a**		
1996						
Crested	156	152	155	140	**151**	**a**
Native	140	119	142	178	**144**	**a**
Mean	**148**	**135**	**148**	**159**		
	a	**a**	**a**	**a**		
1997						
Crested	220	211	198	211	**210**	**a**
Native	231	211	232	225	**225**	**a**
Mean	**225**	**211**	**215**	**218**		
	a	**a**	**a**	**a**		
1998						
Crested	190	188	190	189	**189**	**a**
Native	175	185	186	242	**196**	**a**
Mean	**183**	**187**	**188**	**215**		
	a	**a**	**a**	**a**		
1999						
Crested	248	219	211	176	**214**	**a**
Native	232	233	208	242	**229**	**a**
Mean	**240**	**226**	**210**	**209**		
	a	**a**	**a**	**a**		
2000						
Crested	119	109	135	120	**121**	**a**
Native	108	104	106	103	**105**	**a**
Mean	**113**	**106**	**121**	**112**		
	a	**a**	**a**	**a**		

Table 5 (continued).

Ambient Precipitation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	3	1622	541.0	0.421	0.741
Vegetation	1	858.6	858.6	0.668	0.426
Cap x Vegetation	3	1756	585.4	0.455	0.717
1996					
Cap	3	1667	555.7	0.891	0.467
Vegetation	1	243.2	243.2	0.390	0.541
Cap x Vegetation	3	4187	1395	2.238	0.123
1997					
Cap	3	665.2	221.7	0.448	0.722
Vegetation	1	1270	1270	2.568	0.129
Cap x Vegetation	3	920.1	306.7	0.620	0.612
1998					
Cap	3	3976	1325	1.287	0.313
Vegetation	1	348.5	348.5	0.338	0.569
Cap x Vegetation	3	4250	1416	1.376	0.286
1999					
Cap	3	3897	1299	0.367	0.778
Vegetation	1	1368	1368	0.387	0.543
Cap x Vegetation	3	5813	1937	0.548	0.657
2000					
Cap	3	620.4	206.8	0.407	0.750
Vegetation	1	1518	1518	2.987	0.103
Cap x Vegetation	3	470.5	156.8	0.309	0.819

Table 5 (continued).

B. Summer Irrigation

	Soil Only	Shallow Biobarrier	Deep Biobarrier	RCRA	**Mean**	
1995						
Crested	362	299	377	332	**342**	**a**
Native	334	310	332	292	**317**	**a**
Mean	**348**	**304**	**354**	**312**		
	a	**a**	**a**	**a**		
1996						
Crested	372	428	409	387	**399**	**a**
Native	424	396	407	423	**412**	**a**
Mean	**398**	**412**	**408**	**405**		
	a	**a**	**a**	**a**		
1997						
Crested	399	396	417	389	**400**	**a**
Native	428	396	412	419	**414**	**a**
Mean	**414**	**396**	**415**	**404**		
	a	**a**	**a**	**a**		
1998						
Crested	344	353	357	361	**354**	**a**
Native	372	369	359	406	**376**	**a**
Mean	**358**	**361**	**358**	**384**		
	a	**a**	**a**	**a**		
1999						
Crested	341	360	370	374	**361**	**a**
Native	385	424	407	413	**407**	**b**
Mean	**363**	**392**	**389**	**394**		
	a	**a**	**a**	**a**		
2000						
Crested	324	325	326	344	**330**	**a**
Native	317	327	354	318	**329**	**a**
Mean	**321**	**326**	**340**	**331**		
	a	**a**	**a**	**a**		

Table 5 (continued).

Summer Irrigation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	3	11375	3791	3.864	**0.030**
Vegetation	1	3805	3805	3.879	0.066
Cap x Vegetation	3	2953	984.3	1.003	0.417
1996					
Cap	3	652.5	217.5	0.109	0.954
Vegetation	1	1060	1060	0.532	0.476
Cap x Vegetation	3	6411	2137	1.072	0.389
1997					
Cap	3	1349	450.0	0.562	0.648
Vegetation	1	1132	1132	1.413	0.252
Cap x Vegetation	3	1514	504.7	0.630	0.606
1998					
Cap	3	2750	916.7	1.045	0.400
Vegetation	1	3023	3023	3.445	0.082
Cap x Vegetation	3	1497	499.1	0.569	0.644
1999					
Cap	3	3745	1248	0.481	0.700
Vegetation	1	12578	12578	4.842	**0.043**
Cap x Vegetation	3	671.0	223.7	0.086	0.967
2000					
Cap	3	1232	411.0	0.975	0.429
Vegetation	1	2.338	2.338	0.006	0.942
Cap x Vegetation	3	2291	764.0	1.812	0.186

Table 5 (continued).

C. Fall/Spring Irrigation

	Soil Only	Shallow Biobarrier	Deep Biobarrier	RCRA	**Mean**	
1995*						
Crested	710	687	681	818	**724**	
Native	784	719	818	777	**775**	
Mean	**747**	**703**	**749**	**798**		
1996*						
Crested	262	198	208	179	**212**	
Native	250	244	259	200	**238**	
Mean	**256**	**221**	**234**	**190**		
1997						
Crested	444	317	397	375	**384**	**a**
Native	399	375	382	334	**373**	**a**
Mean	**422**	**346**	**390**	**355**		
	a	**a**	**a**	**a**		
1998						
Crested	247	245	225	233	**238**	**a**
Native	296	229	267	251	**261**	**b**
Mean	**272**	**237**	**246**	**242**		
	a	**a**	**a**	**a**		
1999						
Crested	274	218	248	189	**232**	**a**
Native	344	353	381	196	**318**	**b**
Mean	**309**	**286**	**315**	**193**		
	a	**a**	**a**	**b**		
2000						
Crested	323	290	305	280	**299**	**a**
Native	286	286	306	289	**292**	**a**
Mean	**305**	**288**	**305**	**284**		
	a	**a**	**a**	**a**		

*Insufficient data available to perform two-way ANOVA.

Table 5 (continued).

Fall/Spring Irrigation, Two-Way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1997					
Cap	3	21734	7244	3.299	**0.048**
Vegetation	1	711.8	711.8	0.324	0.577
Cap x Vegetation	3	10189	3396	1.546	0.241
1998					
Cap	3	4276	1425	2.223	0.125
Vegetation	1	3210	3210	5.008	**0.040**
Cap x Vegetation	3	3912	1304	2.034	0.150
1999					
Cap	3	57587	19195	30.732	**<0.001**
Vegetation	1	44611	44611	71.421	**<0.001**
Cap x Vegetation	3	16705	5568	8.915	**0.001**
2000					
Cap	3	2141	713.8	2.351	0.111
Vegetation	1	354.6	354.6	1.168	0.296
Cap x Vegetation	3	1844	614.7	2.025	0.151

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Table 6. Mean estimates of volumetric soil water content (%) at the lower limit of extraction by plants for crested-wheatgrass and native vegetation under three irrigation treatments in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. For the analyses, data for different cap-types were pooled. P values show results of one-way ANOVA's; means underscored by different letters are significantly different at P = 0.05 based on Tukey's multiple comparison test. Significant P values are in bold typeface.

Crested Wheatgrass

	Ambient	Summer	Fall/Spring	P Value
1995	13.8	14.5	22.4	**<0.001**
	a	a	b	
1996	14.7	18.3	18.4	**0.008**
	a	b	b	
1997	15.3	19.0	17.9	**<0.001**
	a	b	b	
1998	15.5	19.4	18.4	**<0.001**
	a	b	b	
1999	16.9	18.6	20.9	**0.007**
	a	ab	b	
2000	15.5	17.8	18.4	**0.006**
	a	b	b	

Native Vegetation

	Ambient	Summer	Fall/Spring	P Value
1995	13.9	13.8	22.4	**<0.001**
	a	a	b	
1996	15.1	16.7	19.6	**0.009**
	a	ab	b	
1997	15.5	16.1	15.7	0.41
	a	a	a	
1998	15.4	16.2	15.5	0.27
	a	a	a	
1999	15.1	15.5	15.9	0.52
	a	a	a	
2000	15.0	15.8	14.9	0.14
	a	a	a	

Table 7. Mean end-of-season soil moisture content (%) in the top 0.5 m of the soil profile for soil-only and shallow-biobarrier caps under (A) ambient precipitation, (B) summer irrigation, and (C) fall/spring irrigation in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Crested refers to crested-wheatgrass vegetation; native refers to native vegetation. Vegetation means followed by different letters, or cap-type means underscored by different letters, are significantly different at P = 0.05 based on results of Tukey's multiple comparisons tests following two-way ANOVA's. Results of two-way ANOVA's are shown for each irrigation treatment following the table of means. In ANOVA tables, significant P values are in bold typeface.

A. Ambient Precipitation

	Soil Only	Shallow Biobarrier	**Mean**	
1995				
Crested	12.0	9.5	**10.7**	**a**
Native	11.9	9.2	**10.5**	**a**
Mean	**11.9**	**9.3**		
	a	**b**		
1996				
Crested	12.8	9.8	**11.3**	**a**
Native	12.1	10.2	**11.1**	**a**
Mean	**12.4**	**10.0**		
	a	**b**		
1997				
Crested	14.2	11.0	**12.6**	**a**
Native	13.6	11.5	**12.5**	**a**
Mean	**13.9**	**11.2**		
	a	**b**		
1998				
Crested	14.2	10.4	**12.3**	**a**
Native	13.4	10.7	**12.1**	**a**
Mean	**13.8**	**10.5**		
	a	**b**		
1999				
Crested	14.6	9.8	**12.2**	**a**
Native	13.6	9.7	**11.6**	**a**
Mean	**14.1**	**9.7**		
	a	**b**		
2000				
Crested	13.9	9.8	**11.9**	**a**
Native	13.1	9.9	**11.5**	**a**
Mean	**13.5**	**9.9**		
	a	**b**		

Table 7 (continued).

Ambient Precipitation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	20.44	20.44	13.017	**0.007**
Vegetation	1	0.137	0.137	0.087	0.776
Cap x Vegetation	1	0.0243	0.0243	0.016	0.904
1996					
Cap	1	17.91	17.91	5.522	**0.047**
Vegetation	1	0.0901	0.0901	0.028	0.872
Cap x Vegetation	1	1.056	1.056	0.326	0.584
1997					
Cap	1	21.17	21.17	5.565	**0.046**
Vegetation	1	0.00213	0.00213	0.001	0.982
Cap x Vegetation	1	0.832	0.832	0.219	0.653
1998					
Cap	1	31.66	31.66	7.282	**0.027**
Vegetation	1	0.156	0.156	0.036	0.854
Cap x Vegetation	1	0.913	0.913	0.210	0.659
1999					
Cap	1	56.72	56.72	25.451	**<0.001**
Vegetation	1	0.891	0.891	0.400	0.545
Cap x Vegetation	1	0.612	0.612	0.275	0.614
2000					
Cap	1	39.24	39.24	11.922	**0.009**
Vegetation	1	0.480	0.480	0.146	0.712
Cap x Vegetation	1	0.563	0.563	0.171	0.690

Table 7 (continued).

B. Summer Irrigation

	Soil Only	Shallow Biobarrier	**Mean**	
1995				
Crested	11.8	9.3	**10.5**	**a**
Native	10.3	9.1	**9.7**	**a**
Mean	**11.1**	**9.2**		
	a	**a**		
1996				
Crested	17.4	12.6	**15.0**	**a**
Native	14.2	12.5	**13.4**	**a**
Mean	**15.8**	**12.5**		
	a	**b**		
1997				
Crested	17.4	14.0	**15.7**	**a**
Native	14.6	12.6	**13.6**	**a**
Mean	**16.0**	**13.3**		
	a	**a**		
1998				
Crested	18.1	14.5	**16.3**	**a**
Native	15.1	12.7	**13.9**	**a**
Mean	**16.6**	**13.6**		
	a	**b**		
1999				
Crested	17.7	12.9	**15.3**	**a**
Native	14.6	12.1	**13.4**	**a**
Mean	**16.1**	**12.5**		
	a	**b**		
2000				
Crested	16.8	11.9	**14.3**	**a**
Native	14.5	12.0	**13.2**	**a**
Mean	**15.6**	**11.9**		
	a	**b**		

Table 7 (continued).

Summer Irrigation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	10.25	10.25	3.924	0.083
Vegetation	1	2.009	2.009	0.769	0.406
Cap x Vegetation	1	1.235	1.235	0.473	0.511
1996					
Cap	1	32.41	32.41	9.025	**0.017**
Vegetation	1	7.938	7.938	2.211	0.175
Cap x Vegetation	1	7.146	7.146	1.990	0.196
1997					
Cap	1	22.22	22.22	4.924	0.057
Vegetation	1	12.51	12.51	2.771	0.135
Cap x Vegetation	1	1.577	1.577	0.349	0.571
1998					
Cap	1	27.51	27.51	5.747	**0.043**
Vegetation	1	17.16	17.16	3.584	0.095
Cap x Vegetation	1	0.946	0.946	0.198	0.668
1999					
Cap	1	39.90	39.90	5.458	**0.048**
Vegetation	1	10.94	10.94	1.497	0.256
Cap x Vegetation	1	3.831	3.831	0.524	0.490
2000					
Cap	1	40.78	40.78	7.267	**0.027**
Vegetation	1	3.521	3.521	0.628	0.451
Cap x Vegetation	1	4.368	4.368	0.779	0.403

Table 7 (continued)

C. Fall/Spring Irrigation

	Soil Only	Shallow Biobarrier	**Mean**	
1995				
Crested	18.4	15.9	**17.2**	**a**
Native	19.9	16.9	**18.4**	**a**
Mean	**19.2**	**16.4**		
	a	**b**		
1996				
Crested	12.9	11.0	**11.9**	**a**
Native	17.8	15.6	**16.7**	**a**
Mean	**15.3**	**13.3**		
	a	**a**		
1997				
Crested	13.4	11.7	**12.6**	**a**
Native	14.3	11.9	**13.1**	**a**
Mean	**13.9**	**11.8**		
	a	**b**		
1998				
Crested	14.4	11.4	**12.9**	**a**
Native	13.7	12.4	**13.0**	**a**
Mean	**14.0**	**11.9**		
	a	**b**		
1999				
Crested	15.9	10.9	**13.4**	**a**
Native	13.2	10.4	**11.8**	**a**
Mean	**14.6**	**10.6**		
	a	**b**		
2000				
Crested	14.3	10.0	**12.1**	**a**
Native	13.1	10.5	**11.8**	**a**
Mean	**13.7**	**10.2**		
	a	**b**		

Table 7 (continued).

Fall/Spring Irrigation, Two-Way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	23.97	23.97	6.778	**0.031**
Vegetation	1	4.613	4.613	1.304	0.286
Cap x Vegetation	1	0.198	0.198	0.056	0.819
1996					
Cap	1	12.44	12.44	0.618	0.455
Vegetation	1	67.02	67.02	3.327	0.106
Cap x Vegetation	1	0.0533	0.0533	0.003	0.960
1997					
Cap	1	13.06	13.06	5.612	**0.045**
Vegetation	1	0.897	0.897	0.385	0.552
Cap x Vegetation	1	0.449	0.449	0.193	0.672
1998					
Cap	1	14.04	14.04	5.803	**0.043**
Vegetation	1	0.0432	0.0432	0.018	0.897
Cap x Vegetation	1	2.202	2.202	0.910	0.368
1999					
Cap	1	46.37	46.37	9.548	**0.015**
Vegetation	1	7.254	7.254	1.494	0.256
Cap x Vegetation	1	3.707	3.707	0.763	0.408
2000					
Cap	1	34.88	34.88	13.648	**0.006**
Vegetation	1	0.354	0.354	0.138	0.720
Cap x Vegetation	1	2.202	2.202	0.861	0.381

Table 8. Mean end-of-season soil moisture content (%) in the bottom 1.5 m of the soil profile for soil-only and shallow-biobarrier caps under (A) ambient precipitation, (B) summer irrigation, and (C) fall/spring irrigation. Crested refers to crested-wheatgrass vegetation; native refers to native vegetation. Vegetation means followed by different letters, or cap-type means underscored by different letters, are significantly different at P = 0.05 based on results of Tukey's multiple comparisons tests following two-way ANOVA's. Results of two-way ANOVA's are shown for each irrigation treatment following the table of means. In ANOVA tables, significant P values are in bold typeface.

A. Ambient Precipitation

	Soil Only	Shallow Biobarrier	**Mean**	
1995				
Crested	15.2	16.9	**16.0**	**a**
Native	15.2	15.0	**15.1**	**a**
Mean	**15.2**	**15.9**		
	a	**a**		
1996				
Crested	16.0	17.3	**16.6**	**a**
Native	16.6	16.6	**16.6**	**a**
Mean	**16.3**	**16.9**		
	a	**a**		
1997				
Crested	16.0	17.3	**16.7**	**a**
Native	16.2	16.5	**16.4**	**a**
Mean	**16.1**	**16.9**		
	a	**a**		
1998				
Crested	16.1	17.1	**16.6**	**a**
Native	16.6	16.4	**16.5**	**a**
Mean	**16.4**	**16.7**		
	a	**a**		
1999				
Crested	19.5	17.5	**18.5**	**a**
Native	17.2	16.0	**16.6**	**a**
Mean	**18.4**	**16.8**		
	a	**a**		
2000				
Crested	17.8	17.1	**17.4**	**a**
Native	16.1	16.2	**16.2**	**a**
Mean	**17.0**	**16.6**		
	a	**a**		

Table 8 (continued).

Ambient Precipitation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	1.740	1.740	0.975	0.352
Vegetation	1	2.439	2.439	1.367	0.276
Cap x Vegetation	1	2.679	2.679	1.501	0.255
1996					
Cap	1	1.261	1.261	0.398	0.546
Vegetation	1	0.00368	0.00368	0.001	0.974
Cap x Vegetation	1	1.340	1.340	0.423	0.534
1997					
Cap	1	1.794	1.794	0.408	0.541
Vegetation	1	0.213	0.213	0.049	0.831
Cap x Vegetation	1	0.635	0.635	0.144	0.714
1998					
Cap	1	0.433	0.433	0.142	0.716
Vegetation	1	0.0616	0.0616	0.020	0.890
Cap x Vegetation	1	1.153	1.153	0.379	0.555
1999					
Cap	1	7.442	7.442	1.263	0.249
Vegetation	1	11.04	11.04	1.873	0.208
Cap x Vegetation	1	0.468	0.468	0.079	0.785
2000					
Cap	1	0.323	0.323	0.114	0.745
Vegetation	1	4.928	4.928	1.735	0.0224
Cap x Vegetation	1	0.414	0.414	0.146	0.712

Table 8 (continued).

B. Summer Irrigation

	Soil Only	Shallow Biobarrier	**Mean**	
1995				
Crested	14.4	18.8	**16.6**	**a**
Native	14.5	15.4	**14.9**	**a**
Mean	**14.5**	**17.1**		
	a	**b**		
1996				
Crested	18.0	17.9	**18.0**	**a**
Native	16.7	17.9	**17.3**	**a**
Mean	**17.4**	**17.9**		
	a	**a**		
1997				
Crested	17.9	18.9	**18.4**	**a**
Native	16.6	17.3	**16.9**	**b**
Mean	**17.3**	**18.1**		
	a	**a**		
1998				
Crested	18.3	19.0	**18.7**	**a**
Native	16.6	17.2	**16.9**	**b**
Mean	**17.5**	**18.1**		
	a	**a**		
1999				
Crested	18.2	18.5	**18.4**	**a**
Native	16.2	17.5	**16.8**	**a**
Mean	**17.2**	**18.0**		
	a	**a**		
2000				
Crested	17.5	18.7	**18.1**	**a**
Native	15.9	17.1	**16.5**	**a**
Mean	**16.7**	**17.9**		
	a	**a**		

Table 8 (continued).

Summer Irrigation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	21.36	21.36	6.383	**0.035**
Vegetation	1	8.551	8.551	2.555	0.149
Cap x Vegetation	1	9.100	9.100	2.719	0.138
1996					
Cap	1	0.837	0.837	0.431	0.530
Vegetation	1	1.147	1.147	0.590	0.464
Cap x Vegetation	1	1.380	1.380	0.710	0.424
1997					
Cap	1	1.960	1.930	1.949	0.200
Vegetation	1	6.586	6.586	6.548	**0.034**
Cap x Vegetation	1	0.0520	0.0520	0.052	0.826
1998					
Cap	1	1.374	1.374	0.785	0.402
Vegetation	1	9.612	9.612	5.491	**0.047**
Cap x Vegetation	1	0.00270	0.00270	0.002	0.970
1999					
Cap	1	2.134	2.134	0.858	0.381
Vegetation	1	6.992	6.992	2.812	0.132
Cap x Vegetation	1	0.791	0.791	0.318	0.588
2000					
Cap	1	4.236	4.236	2.136	0.182
Vegetation	1	8.184	8.184	4.126	0.077
Cap x Vegetation	1	0.005	0.005	0.003	0.960

Table 8 (continued).

C. Fall/Spring Irrigation

	Soil Only	Shallow Biobarrier	**Mean**	
1995				
Crested	24.6	24.5	**24.6**	**a**
Native	23.9	24.7	**24.3**	**a**
Mean	**24.3**	**24.6**		
	a	**a**		
1996				
Crested	16.8	24.0	**20.4**	**a**
Native	21.7	21.5	**21.6**	**a**
Mean	**19.2**	**22.7**		
	a	**a**		
1997				
Crested	16.7	23.8	**20.3**	**a**
Native	16.8	17.6	**17.2**	**b**
Mean	**16.7**	**20.7**		
	a	**b**		
1998				
Crested	19.5	23.7	**21.6**	**a**
Native	16.4	17.6	**17.0**	**b**
Mean	**18.0**	**20.7**		
	a	**b**		
1999				
Crested	23.5	27.9	**25.7**	**a**
Native	16.5	17.4	**17.0**	**b**
Mean	**20.0**	**22.6**		
	a	**b**		
2000				
Crested	19.0	26.4	**22.7**	**a**
Native	15.8	17.0	**16.4**	**b**
Mean	**17.4**	**21.7**		
	a	**b**		

Table 8 (continued).

Fall/Spring Irrigation, Two-Way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	0.392	0.392	0.126	0.732
Vegetation	1	0.190	0.190	0.061	0.811
Cap x Vegetation	1	0.816	0.816	0.262	0.622
1996					
Cap	1	37.14	37.14	1.392	0.272
Vegetation	1	4.189	4.189	0.157	0.702
Cap x Vegetation	1	42.08	42.08	1.577	0.245
1997					
Cap	1	47.68	47.68	16.932	**0.003**
Vegetation	1	28.34	28.34	10.063	**0.013**
Cap x Vegetation	1	30.08	30.08	10.683	**0.011**
1998					
Cap	1	22.03	22.03	5.551	**0.046**
Vegetation	1	62.75	62.75	15.808	**0.004**
Cap x Vegetation	1	6.840	6.840	1.723	0.226
1999					
Cap	1	20.88	20.88	14.797	**0.005**
Vegetation	1	227.0	227.0	160.833	**<0.001**
Cap x Vegetation	1	9.346	9.346	6.622	**0.033**
2000					
Cap	1	55.26	55.26	26.875	**<0.001**
Vegetation	1	116.8	116.8	56.784	**<0.001**
Cap x Vegetation	1	28.99	28.99	14.098	**0.006**

Table 9. Mean end-of-season soil moisture content (%) in the top 1 m of the soil profile for soil-only, deep-biobarrier, and RCRA caps under (A) ambient precipitation, (B) summer irrigation, and (C) fall/spring irrigation. Crested refers to crested-wheatgrass vegetation; native refers to native vegetation. Vegetation means followed by different letters, or cap-type means underscored by different letters, are significantly different at P = 0.05 based on results of Tukey's multiple comparisons tests following two-way ANOVA's. Results of two-way ANOVA's are shown for each irrigation treatment following the table of means. In ANOVA tables, significant P values are in bold typeface.

A. Ambient Precipitation

	Soil Only	Deep Biobarrier	RCRA	**Mean**	
1995					
Crested	13.1	11.0	12.5	**12.2**	**a**
Native	12.9	11.7	13.8	**12.8**	**a**
Mean	**13.0**	**11.3**	**13.1**		
	a	**b**	**a**		
1996					
Crested	13.9	11.5	13.6	**13.0**	**a**
Native	13.7	12.6	14.7	**13.6**	**a**
Mean	**13.8**	**12.0**	**14.2**		
	ab	**a**	**b**		
1997					
Crested	14.7	12.9	15.0	**14.2**	**a**
Native	14.5	13.3	15.8	**14.5**	**a**
Mean	**14.6**	**13.1**	**15.4**		
	ab	**a**	**b**		
1998					
Crested	14.8	13.9	14.8	**14.5**	**a**
Native	14.3	13.2	15.6	**14.4**	**a**
Mean	**14.5**	**13.5**	**15.2**		
	a	**a**	**a**		
1999					
Crested	16.5	14.1	16.3	**15.6**	**a**
Native	14.9	14.0	14.4	**14.4**	**a**
Mean	**15.7**	**14.0**	**15.4**		
	a	**a**	**a**		
2000					
Crested	14.9	12.5	14.2	**13.9**	**a**
Native	14.0	12.8	15.1	**13.9**	**a**
Mean	**14.5**	**12.6**	**14.6**		
	a	**b**	**a**		

Table 9 (continued).

Ambient Precipitation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	2	12.11	6.055	6.063	**0.015**
Vegetation	1	1.508	1.508	1.510	0.243
Cap x Vegetation	2	1.774	0.887	0.888	0.437
1996					
Cap	2	15.43	7.713	5.868	**0.017**
Vegetation	1	1.811	1.811	1.378	0.263
Cap x Vegetation	2	1.858	0.929	0.707	0.513
1997					
Cap	2	16.74	8.372	5.237	**0.023**
Vegetation	1	0.423	0.423	0.265	0.616
Cap x Vegetation	2	0.690	0.345	0.216	0.809
1998					
Cap	2	8.767	4.383	1.451	0.273
Vegetation	1	0.0882	0.0882	0.029	0.867
Cap x Vegetation	2	2.073	1.036	0.343	0.716
1999					
Cap	2	9.115	4.557	1.342	0.298
Vegetation	1	6.625	6.625	1.950	0.188
Cap x Vegetation	2	2.658	1.329	0.391	0.685
2000					
Cap	2	14.51	7.256	7.921	**0.006**
Vegetation	1	0.0374	0.0374	0.041	0.843
Cap x Vegetation	2	2.584	1.292	1.140	0.282

Table 9 (continued).

B. Summer Irrigation

	Soil Only	Deep Biobarrier	RCRA	**Mean**	
1995					
Crested	12.6	10.2	15.1	**12.7**	**a**
Native	11.8	11.0	14.3	**12.4**	**a**
Mean	**12.2**	**10.6**	**14.7**		
	ab	**a**	**b**		
1996					
Crested	18.3	17.9	21.5	**19.2**	**a**
Native	15.0	14.7	17.9	**15.9**	**b**
Mean	**16.6**	**16.3**	**19.7**		
	a	**a**	**b**		
1997					
Crested	17.9	19.2	22.4	**19.8**	**a**
Native	15.2	14.3	16.4	**15.3**	**b**
Mean	**16.5**	**16.7**	**19.4**		
	a	**a**	**b**		
1998					
Crested	18.5	20.7	22.2	**20.5**	**a**
Native	15.5	14.5	16.3	**15.4**	**b**
Mean	**17.0**	**17.6**	**19.3**		
	a	**a**	**a**		
1999					
Crested	18.2	19.2	21.1	**19.5**	**a**
Native	14.8	13.3	15.6	**14.6**	**b**
Mean	**16.5**	**16.3**	**18.4**		
	a	**a**	**a**		
2000					
Crested	17.2	17.7	19.2	**18.0**	**a**
Native	14.8	13.4	16.6	**14.9**	**b**
Mean	**16.0**	**15.6**	**17.9**		
	a	**a**	**a**		

Table 9 (continued).

Summer Irrigation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	2	51.23	25.61	4.481	**0.035**
Vegetation	1	0.376	0.376	0.066	0.802
Cap x Vegetation	2	2.734	1.367	0.239	0.791
1996					
Cap	2	42.04	21.02	5.472	**0.020**
Vegetation	1	50.37	50.37	13.112	**0.004**
Cap x Vegetation	2	0.0765	0.0383	0.010	0.990
1997					
Cap	2	31.36	15.68	7.437	**0.008**
Vegetation	1	91.67	91.67	43.477	**<0.001**
Cap x Vegetation	2	8.427	4.213	1.998	0.178
1998					
Cap	2	16.75	8.38	2.410	0.132
Vegetation	1	113.8	113.8	32.742	**<0.001**
Cap x Vegetation	2	8.972	4.486	1.291	0.311
1999					
Cap	2	15.54	7.770	0.866	0.446
Vegetation	1	109.0	109.0	12.140	**0.005**
Cap x Vegetation	2	5.391	2.695	0.300	0.746
2000					
Cap	2	18.27	9.133	1.249	0.322
Vegetation	1	43.21	43.21	5.909	**0.032**
Cap x Vegetation	2	3.228	1.614	0.221	0.805

Table 9 (continued).

C. Fall/Spring Irrigation

	Soil Only	Deep Biobarrier	RCRA	**Mean**	
1995					
Crested	21.0	22.3	20.6	**21.3**	**a**
Native	21.2	19.6	22.5	**21.1**	**a**
Mean	**21.1**	**21.0**	**21.6**		
	a	**a**	**a**		
1996					
Crested	14.2	16.5	15.9	**15.5**	**a**
Native	19.0	16.5	18.5	**18.0**	**a**
Mean	**16.6**	**16.5**	**17.2**		
	a	**a**	**a**		
1997					
Crested	14.5	13.2	17.6	**15.1**	**a**
Native	15.1	12.8	15.5	**14.4**	**a**
Mean	**14.8**	**13.0**	**16.6**		
	ab	**a**	**b**		
1998					
Crested	16.1	14.5	17.1	**15.9**	**a**
Native	14.5	12.2	15.4	**14.0**	**a**
Mean	**15.3**	**13.3**	**16.2**		
	a	**a**	**a**		
1999					
Crested	18.2	16.9	16.1	**17.1**	**a**
Native	14.4	12.4	16.9	**14.6**	**b**
Mean	**16.3**	**14.7**	**16.5**		
	a	**a**	**a**		
2000					
Crested	15.5	13.3	15.5	**14.7**	**a**
Native	13.9	12.4	14.5	**13.6**	**a**
Mean	**14.7**	**12.8**	**15.0**		
	a	**a**	**a**		

Table 9 (continued).

Fall/Spring Irrigation, Two-Way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	2	1.149	0.574	0.211	0.812
Vegetation	1	0.130	0.130	0.048	0.831
Cap x Vegetation	2	16.39	8.195	3.015	0.087
1996					
Cap	2	1.431	0.715	0.021	0.979
Vegetation	1	27.33	27.33	0.805	0.387
Cap x Vegetation	2	17.85	8.923	0.263	0.773
1997					
Cap	2	38.34	19.17	4.625	**0.032**
Vegetation	1	2.020	2.020	0.487	0.498
Cap x Vegetation	2	5.186	2.593	0.626	0.552
1998					
Cap	2	26.08	13.04	3.656	0.058
Vegetation	1	15.89	15.89	4.454	0.056
Cap x Vegetation	2	0.511	0.256	0.072	0.931
1999					
Cap	2	12.23	6.116	1.047	0.381
Vegetation	1	28.08	28.08	4.805	**0.049**
Cap x Vegetation	2	24.68	12.34	2.112	0.164
2000					
Cap	2	16.72	8.358	3.599	0.060
Vegetation	1	6.044	6.044	2.602	0.133
Cap x Vegetation	2	0.392	0.196	0.084	0.920

Table 10. Mean-end-of season soil moisture content (%) in the bottom 1 m of the soil profile for soil-only and deep-biobarrier caps under (A) ambient precipitation, (B) summer irrigation, and (C) fall/spring irrigation. Crested refers to crested-wheatgrass vegetation; native refers to native vegetation. Vegetation means followed by different letters, or cap-type means underscored by different letters, are significantly different at P = 0.05 based on results of Tukey's multiple comparisons tests following two-way ANOVA's. Results of two-way ANOVA's are shown for each irrigation treatment following the table of means. In ANOVA tables, significant P values are in bold typeface.

A. Ambient Precipitation

	Soil Only	Deep Biobarrier	**Mean**	
1995				
Crested	15.7	15.7	**15.7**	**a**
Native	15.9	16.5	**16.2**	**a**
Mean	**15.8**	**16.1**		
	a	**a**		
1996				
Crested	16.5	17.5	**17.0**	**a**
Native	17.3	17.6	**17.4**	**a**
Mean	**16.9**	**17.5**		
	a	**a**		
1997				
Crested	16.5	17.5	**17.0**	**a**
Native	16.7	17.5	**17.1**	**a**
Mean	**16.6**	**17.5**		
	a	**a**		
1998				
Crested	16.5	18.7	**17.6**	**a**
Native	17.4	17.5	**17.4**	**a**
Mean	**16.9**	**18.1**		
	a	**a**		
1999				
Crested	20.2	21.1	**20.7**	**a**
Native	17.7	16.9	**17.3**	**a**
Mean	**19.0**	**19.0**		
	a	**a**		
2000				
Crested	17.2	19.5	**18.3**	**a**
Native	16.8	17.0	**16.9**	**a**
Mean	**17.0**	**18.2**		
	a	**a**		

Table 10 (continued).

Ambient Precipitation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	0.307	0.307	0.165	0.695
Vegetation	1	0.770	0.770	0.413	0.538
Cap x Vegetation	1	0.252	0.252	0.135	0.722
1996					
Cap	1	1.313	1.313	0.557	0.477
Vegetation	1	0.525	0.525	0.223	0.650
Cap x Vegetation	1	0.476	0.476	0.202	0.665
1997					
Cap	1	2.530	2.530	0.585	0.466
Vegetation	1	0.0331	0.0331	0.008	0.932
Cap x Vegetation	1	0.0154	0.0154	0.004	0.954
1998					
Cap	1	4.118	4.118	1.457	0.262
Vegetation	1	0.118	0.118	0.042	0.843
Cap x Vegetation	1	3.070	3.070	1.086	0.328
1999					
Cap	1	0.0147	0.0147	0.001	0.976
Vegetation	1	33.74	33.74	2.252	0.172
Cap x Vegetation	1	2.117	2.117	0.141	0.717
2000					
Cap	1	4.902	4.902	0.486	0.505
Vegetation	1	6.380	6.380	0.633	0.449
Cap x Vegetation	1	3.488	3.488	0.346	0.573

Table 10 (continued).

B. Summer Irrigation

	Soil Only	Deep Biobarrier	**Mean**	
1995				
Crested	14.9	15.0	**15.0**	**a**
Native	15.1	16.0	**15.6**	**a**
Mean	**15.0**	**15.5**		
	a	**a**		
1996				
Crested	17.5	16.8	**17.1**	**a**
Native	17.2	17.6	**17.4**	**a**
Mean	**17.3**	**17.2**		
	a	**a**		
1997				
Crested	17.7	17.4	**17.6**	**a**
Native	17.0	17.4	**17.2**	**a**
Mean	**17.4**	**17.4**		
	a	**a**		
1998				
Crested	18.0	17.6	**17.8**	**a**
Native	17.0	17.8	**17.4**	**a**
Mean	**17.5**	**17.7**		
	a	**a**		
1999				
Crested	17.9	17.3	**17.6**	**a**
Native	16.8	16.0	**16.4**	**a**
Mean	**17.3**	**16.6**		
	a	**a**		
2000				
Crested	17.5	17.7	**17.6**	**a**
Native	16.4	17.4	**16.9**	**a**
Mean	**16.9**	**17.5**		
	a	**a**		

Table 10 (continued).

Summer Irrigation, Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	0.677	0.677	0.570	0.472
Vegetation	1	1.074	1.074	0.905	0.369
Cap x Vegetation	1	0.460	0.460	0.388	0.551
1996					
Cap	1	0.0444	0.0444	0.029	0.869
Vegetation	1	0.185	0.185	0.120	0.738
Cap x Vegetation	1	0.735	0.735	0.477	0.509
1997					
Cap	1	0.00120	0.00120	0.001	0.976
Vegetation	1	0.368	0.368	0.289	0.605
Cap x Vegetation	1	0.367	0.367	0.289	0.605
1998					
Cap	1	0.0936	0.0936	0.054	0.822
Vegetation	1	0.546	0.546	0.314	0.591
Cap x Vegetation	1	1.129	1.129	0.649	0.444
1999					
Cap	1	1.498	1.498	0.765	0.407
Vegetation	1	4.465	4.465	2.279	0.170
Cap x Vegetation	1	0.0243	0.0243	0.012	0.914
2000					
Cap	1	1.086	1.086	0.648	0.444
Vegetation	1	1.562	1.562	0.932	0.363
Cap x Vegetation	1	0.460	0.460	0.275	0.615

Table 10 (continued).

C. **Fall/Spring Irrigation**

	Soil Only	Deep Biobarrier	**Mean**	
1995				
Crested	25.2	25.4	**25.3**	**a**
Native	24.6	23.3	**24.0**	**a**
Mean	**24.9**	**24.3**		
	a	**a**		
1996				
Crested	17.4	25.9	**21.7**	**a**
Native	22.4	21.7	**22.1**	**a**
Mean	**19.9**	**23.8**		
	a	**a**		
1997				
Crested	17.2	21.3	**19.3**	**a**
Native	17.3	17.2	**17.3**	**b**
Mean	**17.3**	**19.2**		
	a	**b**		
1998				
Crested	20.4	20.9	**20.6**	**a**
Native	17.0	16.9	**17.0**	**b**
Mean	**18.7**	**18.9**		
	a	**a**		
1999				
Crested	25.1	27.3	**26.2**	**a**
Native	17.1	18.0	**17.5**	**b**
Mean	**21.1**	**22.6**		
	a	**a**		
2000				
Crested	20.2	22.6	**21.4**	**a**
Native	16.4	17.0	**16.7**	**b**
Mean	**18.3**	**19.8**		
	a	**a**		

Table 10 (continued).

Fall/Spring Irrigation, Two-Way ANOVA Results

Source of Variation	DF	SS	MS	F	P
1995					
Cap	1	1.033	1.033	0.064	0.807
Vegetation	1	5.307	5.307	0.326	0.584
Cap x Vegetation	1	1.703	1.703	0.105	0.755
1996					
Cap	1	46.34	46.34	1.453	0.262
Vegetation	1	0.418	0.418	0.013	0.912
Cap x Vegetation	1	62.93	62.93	1.973	0.198
1997					
Cap	1	11.64	11.64	6.034	**0.040**
Vegetation	1	11.80	11.80	6.116	**0.039**
Cap x Vegetation	1	13.31	13.31	6.901	**0.030**
1998					
Cap	1	0.105	0.105	0.025	0.879
Vegetation	1	39.97	39.97	9.417	**0.015**
Cap x Vegetation	1	0.307	0.307	0.072	0.795
1999					
Cap	1	7.254	7.254	4.620	0.064
Vegetation	1	223.9	223.9	142.563	**<0.001**
Cap x Vegetation	1	1.435	1.435	0.914	0.367
2000					
Cap	1	6.946	6.946	1.788	0.218
Vegetation	1	66.22	66.22	17.047	**0.003**
Cap x Vegetation	1	2.755	2.755	0.709	0.424

Table 11. A. Average depth of water (mm) applied before drainage was observed or inferred for soil-only, shallow-biobarrier, or deep-biobarrier subplots in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory (see section 3.8 for details). Crested refers to crested-wheatgrass vegetation; native refers to native vegetation.

	Soil Only	Shallow Biobarrier	Deep Biobarrier	**Mean**	
Crested	607	727	717	**684**	**a**
Native	705	726	718	**717**	**a**
Mean	**656**	**727**	**718**		
	a	**a**	**a**		

Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
Cap	2	17742	8871	2.616	0.114
Vegetation	1	4862	4862	1.434	0.254
Cap x Vegetation	2	9609	4804	1.417	0.280

B. Amount of water in the entire soil profile when drainage was observed or inferred for soil-only, shallow-biobarrier, or deep-biobarrier subplots in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory (see section 3.8 details). Crested refers to crested-wheatgrass vegetation; native refers to native vegetation.

	Soil Only	Shallow Biobarrier	Deep Biobarrier	**Mean**	
Crested	579	611	623	**604**	**a**
Native	621	599	608	**610**	**a**
Mean	**600**	**605**	**616**		
	a	**a**	**a**		

Two-way ANOVA Results

Source of Variation	DF	SS	MS	F	P
Cap	2	751.6	375.8	0.460	0.642
Vegetation	1	134.0	134.0	0.164	0.692
Cap x Vegetation	2	3006	1503	1.842	0.201

Table 12. Mean end-of-season soil moisture content (%) before and after the irrigation to failure trials in the spring of 1999 on the four cap configurations and two vegetation types of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Means underscored by different letters are significantly different at P = 0.05 by Tukey's multiple comparison tests following one-way ANOVA's. Significant P values are shown in bold typeface.

	1998	1999	2000	P Value
Crested Wheatgrass				
Soil Only	18.2	20.3	17.8	0.24
	a	a	a	
Shallow Biobarrier	20.6	22.5	22.3	0.27
	a	a	a	
Deep Biobarrier	17.7	21.1	18.0	**0.03**
	a	b	a	
RCRA	17.1	16.4	15.5	0.22
	a	a	a	
Native Vegetation				
Soil Only	15.7	15.9	15.1	**0.05**
	ab	a	b	
Shallow Biobarrier	16.3	16.0	15.4	0.40
	a	a	a	
Deep Biobarrier	14.9	15.2	14.7	0.10
	a	a	a	
RCRA	15.4	13.6	14.5	**0.04**
	a	b	ab	

Table 13. Results of two-way ANOVA's of vegetative cover in 2000 under three precipitation/irrigation regimes with cap type and vegetation type as factors. Means are shown in Figure 38. Significant P values are shown in bold typeface.

Source of Variation	DF	SS	MS	F	P
Ambient Precipitation					
Cap	3	65.085	21.695	0.555	0.652
Vegetation	1	608.617	608.617	15.581	**0.001**
Cap x Vegetation	3	28.048	9.349	0.239	0.868
Summer Irrigation					
Cap	3	166.969	55.656	1.884	0.173
Vegetation	1	2092.914	2092.914	70.854	**<0.001**
Cap x Vegetation	3	54.685	18.228	0.617	0.614
Fall/Spring Irrigation					
Cap	3	551.153	183.718	3.945	**0.028**
Vegetation	1	3749.684	3749.684	80.510	**<0.001**
Cap x Vegetation	3	149.353	49.784	1.069	0.390

Table 14. Mean end-of-season soil moisture content in 1998 for four cap types planted in two vegetation types under three precipitation regimes. Although results were not always statistically significant due to small sample sizes, crested-wheatgrass subplots always had higher mean values than did native subplots under augmented irrigation regimes. Results from 1998 are typical of results from 1996-2000. Significant P values are shown in bold typeface.

	Crested Wheatgrass	Native Species	Difference	P Value
Ambient Precipitation				
Soil Only Cap	15.597	15.783	-0.187	0.914
Shallow Biobarrier Cap	15.430	14.940	0.490	0.707
Deep Biobarrier Cap	16.307	15.343	0.963	0.484
RCRA Cap	14.830	15.643	-0.813	0.173
Summer Irrigation				
Soil Only Cap	18.277	16.203	2.073	0.210
Shallow Biobarrier Cap	17.913	16.090	1.823	0.083
Deep Biobarrier Cap	19.150	16.173	2.977	**0.014**
RCRA Cap	22.217	16.310	5.907	**0.020**
Fall/Spring Irrigation				
Soil Only Cap	18.197	15.693	2.503	0.183
Shallow Biobarrier Cap	20.620	16.303	4.317	**0.024**
Deep Biobarrier Cap	17.687	14.533	3.153	**0.039**
RCRA Cap	17.073	15.367	1.707	0.396

Table 15. Lithium content for nine species on the shallow- and deep-biobarrier plots in the Protective Cap Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. PVC tubes extended below the biobarrier on each shallow- and deep-biobarrier plot (> 1m for shallow biobarriers, >1.5m for deep biobarriers). Lithium chloride was introduced into the soil below the biobarriers through the tubes in June of 2000. Plant tissue samples were collected from plants adjacent to the tubes (within 1m) and from the same species on the opposite side of the subplot (> 5m from the tube) in August of 2000.

Species	Plot	Subplot	Adjacent	Opposite
Shallow Biobarrier			Lithium (mg/kg)	
Agropyron desertorum	2	3	0.80	1.7
Agropyron desertorum	8	2	97	1.6
Agropyron desertorum	8	4	16	0.43
Agropyron desertorum	8	5	4.6	0.30
Agropyron desertorum	8	6	0.39	0.21
Agropyron desertorum	10	1	1.9	0.12
Agropyron desertorum	10	2	1.6	0.12
Artemisia tridentata	2	3	0.51	0.16
Artemisia tridentata	2.	6	0.46	0.17
Artemisia tridentata	8	6	2.7	0.15
Artemisia tridentata	10	2	0.20	0.18
Chrysothamnus nauseosus	2	3	17	0.23
Chrysothamnus nauseosus	8	6	1.7	0.098
Chrysothamnus nauseosus	10	2	3.2	0.12
Elymus lanceolatus	2	6	12	0.30
Krascheninnikovia lanata	2	6	0.14	0.077
Leymus cinerus	2	3	9.1	0.072
Linum perenne	2	6	11	2.2
Deep Biobarrier				
Agropyron desertorum	4	3	0.26	0.17
Agropyron desertorum	4	6	8.6	0.33
Agropyron desertorum	6	5	0.51	0.19
Agropyron desertorum	9	1	1.8	0.27
Artemisia tridentata	4	3	0.36	0.16
Artemisia tridentata	4	6	0.66	0.15
Artemisia tridentata	9	1	0.29	0.14
Chrysothamnus nauseosus	6	5	18	0.17
Chrysothamnus nauseosus	9	1	0.17	0.21
Chrysothamnus viscidiflorus	4	6	8.3	0.46
Chrysothamnus viscidiflorus	9	1	2.1	0.33
Hedysarum boreale	6	5	15	0.35

Table 16. Plant species recommended for planting on evapotranspiration caps at the Idaho National Engineering and Environmental Laboratory. Commercially available cultivars (CV) are listed under source[1]. CS refers to nursery-grown container stock; W refers to transplanting of locally grown materials (wildings; see Shumar and Anderson 1987).

Growth Form &Common Name	**Scientific Name**	**Source**
Shrubs:		
Big sagebrush	*Artemisia tridentata*	Local seed, CS, W
Fringed sagebrush	*Artemisia frigida*	Local or commercial seed, W
Green rabbitbrush	*Chrysothamnus viscidiflorus*	Local seed, CS, W
Winterfat	*Kraschenninnikovia lanata*	CV: Hatch; Local seed, W
Perennial grasses		
Streambank wheatgrass	*Elymus lanceolatus*	CV: Sodar
Thick-spiked wheatgrass	*Elymus lanceolatus*	CV: Bannock
Bluebunch wheatgrass	*Pseudoroegneria spicata*	CV: Goldar, Secar, Whitmar[1]
Western wheatgrass	*Pascopyrum smithii*	CV: Rosana
Great basin wildrye	*Leymus cinereus*	CV: Magnar, Trailhead
Beardless wildrye	*Leymus triticoides*	CV: Shoshone
Perennial forbs		
Northern sweetvetch	*Hedysarum boreale*	Local or commercial seed
Tapertip hawksbeard	*Crepis acuminata*	Local seed
Lupine	*Lupinus argenteus*	Local seed
Scarlet globe-mallow	*Sphaeralcea munroana*	Local or commercial seed

[1]Additional information on cultivars can be found on the USDA web site: http://plants.usda.gov/

[2]New cultivars of winterfat and of bluebunch wheatgrass are being developed by the Plant Materials Center at Aberdeen, Idaho.

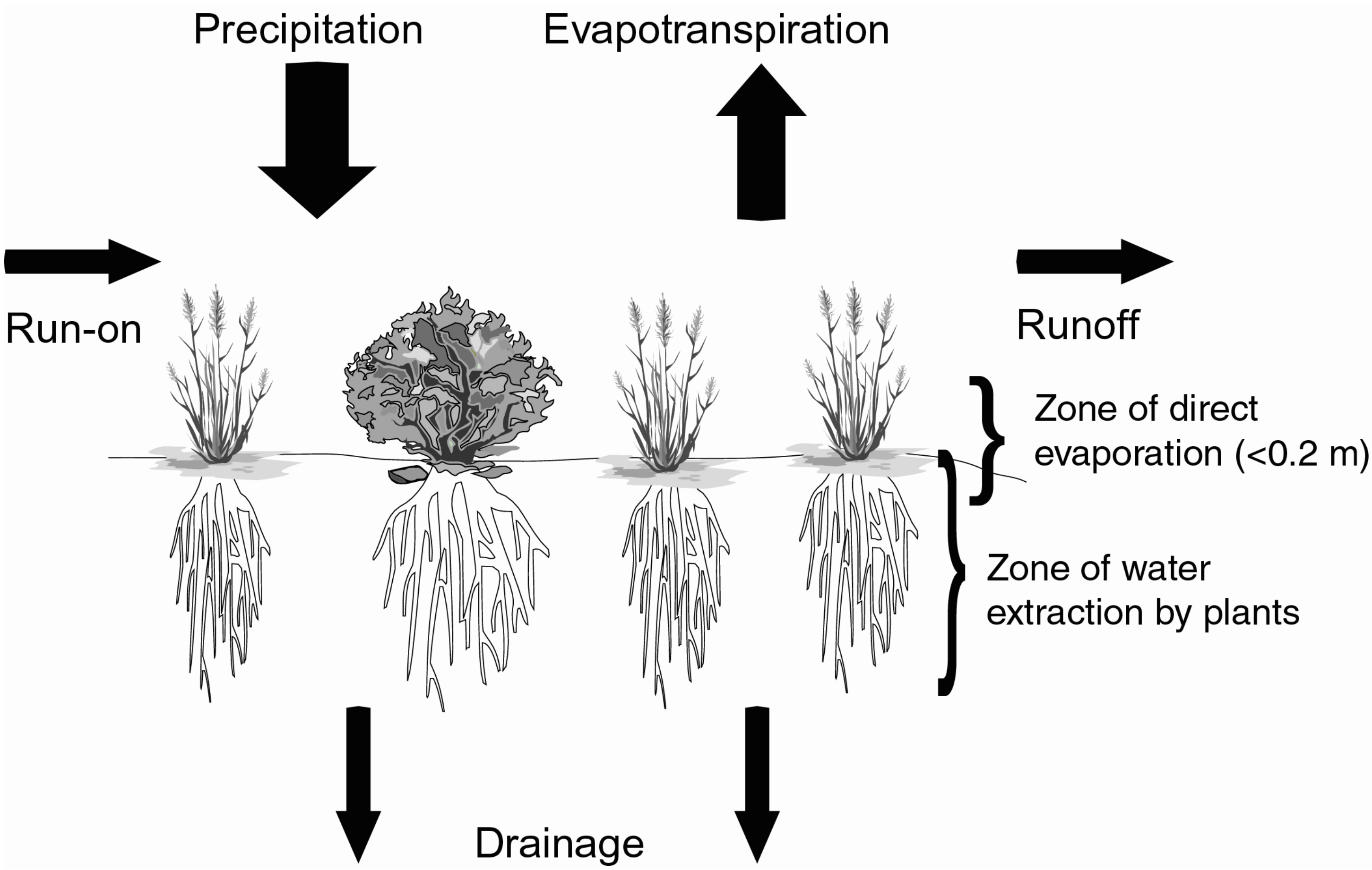


Figure 1. Water balance of a vegetated plot. Plants extract water from throughout the soil profile, to depths that may exceed 2 m in deep soils. In contrast, most water lost by direct evaporation comes from the upper 0.2 m of soil. The combined loss of water by direct evaporation and transpiration by plants is called evapotranspiration. For level, vegetated plots having deep soils in semiarid regions, run-on, runoff, and drainage are negligible, and evapotranspiration will equal precipitation on average over yearly intervals.

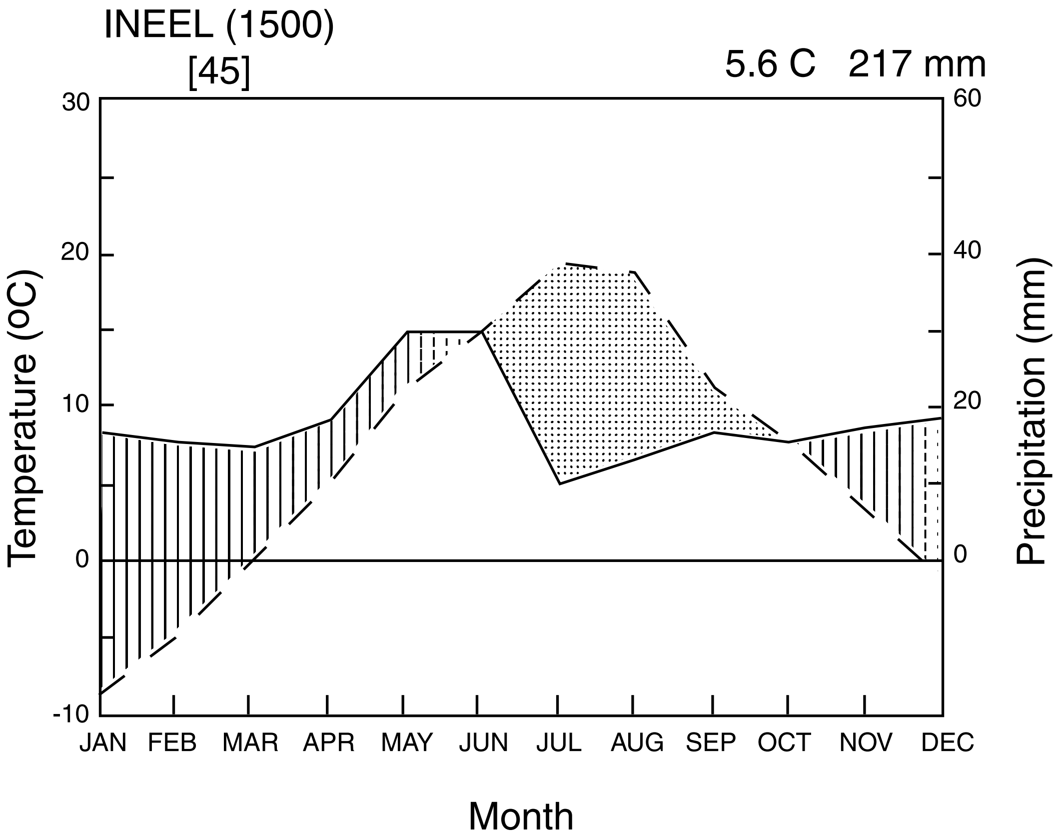


Figure 2. Climate diagram (*sensu* Walter et al. 1975) for the Idaho National Engineering and Environmental Laboratory (INEEL) based on data for 46 years from the Central Facilities Area (U.S. National Oceanic and Atmospheric Administration, Idaho Falls, Idaho, unpublished data). Solid curve depicts mean monthly precipitation; dashed curve shown mean monthly temperatures. Vertical hatching indicates periods when precipitation generally exceeds potential evapotranspiration. Stippled area indicates periods when potential evapotranspiration generally exceed precipitation.

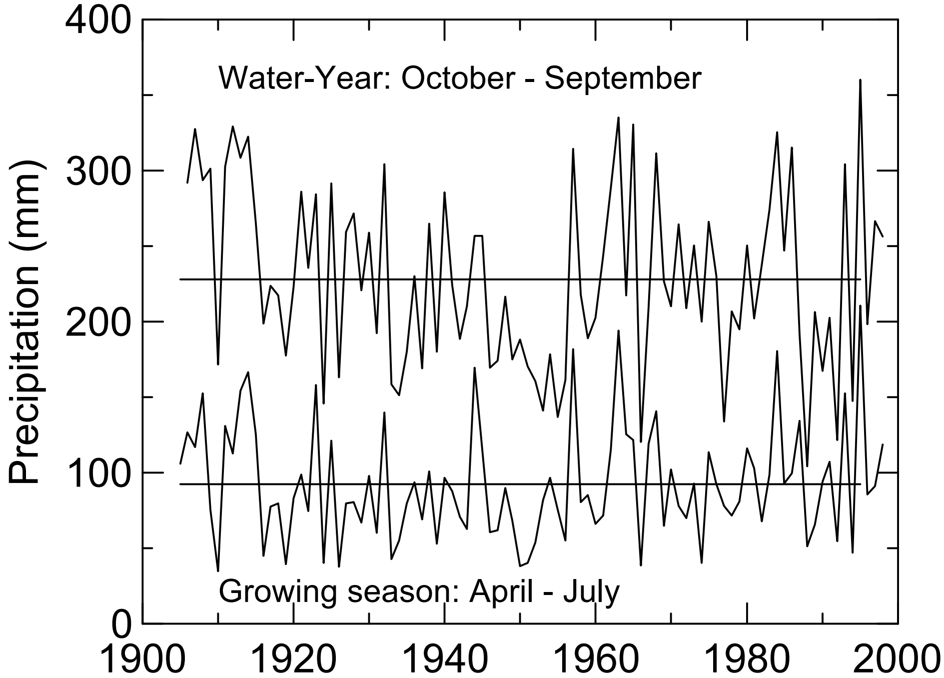


Figure 3. Precipitation data for the Idaho National engineering and Environmental Laboratory (INEEL). Data for years prior to 1950 were estimated using correlations between data from the INEEL Central Facilities Area and nearby locations (see Methods, *Precipitation Data and Estimates*). Upper curve shows water-year (October – September) precipitation; lower curve shows early growing season (April – July) precipitation. Horizontal lines depict long-term means for water-year or growing season precipitation.

Figure 4. Layout (not to scale) of the Protective Cap/Biobarrier Experiment at the Experimental Field Station, Idaho National Engineering and Environmental Laboratory. The 12 main plots are three replicates of the four cap configurations depicted in Figure 5. Each main plots is divided into six subplots representing the two vegetation types and three irrigation treatments (see section 2.0). The position of six caissons is shown as a bold circle between plots. Soil texture data corresponding to each main plot is shown to the right of the layout. cwg = crested wheatgrass vegetation; native = native vegetation.

SUBPLOT NUMBERING

1	3	5
2	4	6

IRRIGATION

ambient	summer	fall/spring

Soil Particle Size Distribution (%)

				Sand	Silt	Clay
PLOT 1	native	cwg	native	17	43	40
RCRA	cwg	native	cwg			
PLOT 2	native	native	cwg	18	45	37
0.5 m barrier	cwg	cwg	native			
PLOT 3	cwg	native	native	18	47	35
soil only	native	cwg	cwg			
PLOT 4	cwg	native	cwg	19	49	32
1 m barrier	native	cwg	native			
PLOT 5	cwg	native	native	18	45	37
soil only	native	cwg	cwg			
PLOT 6	cwg	cwg	native	19	48	33
1 m barrier	native	native	cwg			
PLOT 7	cwg	native	cwg	21	52	27
RCRA	native	cwg	native			
PLOT 8	native	native	cwg	19	48	33
0.5 m barrier	cwg	cwg	native			
PLOT 9	native	cwg	native	18	48	34
1 m barrier	cwg	native	cwg			
PLOT 10	cwg	native	cwg	23	52	25
0.5 m barrier	native	cwg	native			
PLOT 11	native	cwg	cwg	21	55	24
soil only	cwg	native	native			
PLOT 12	native	cwg	native	17	45	38
RCRA	cwg	native	cwg			

Figure 5. Schematic diagram of vertical sections of the four cap configurations in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Biological intrusion barriers (biobarriers) consisted of a 0.3-m depth of cobble sandwiched between 0.1-m depths of gravel.

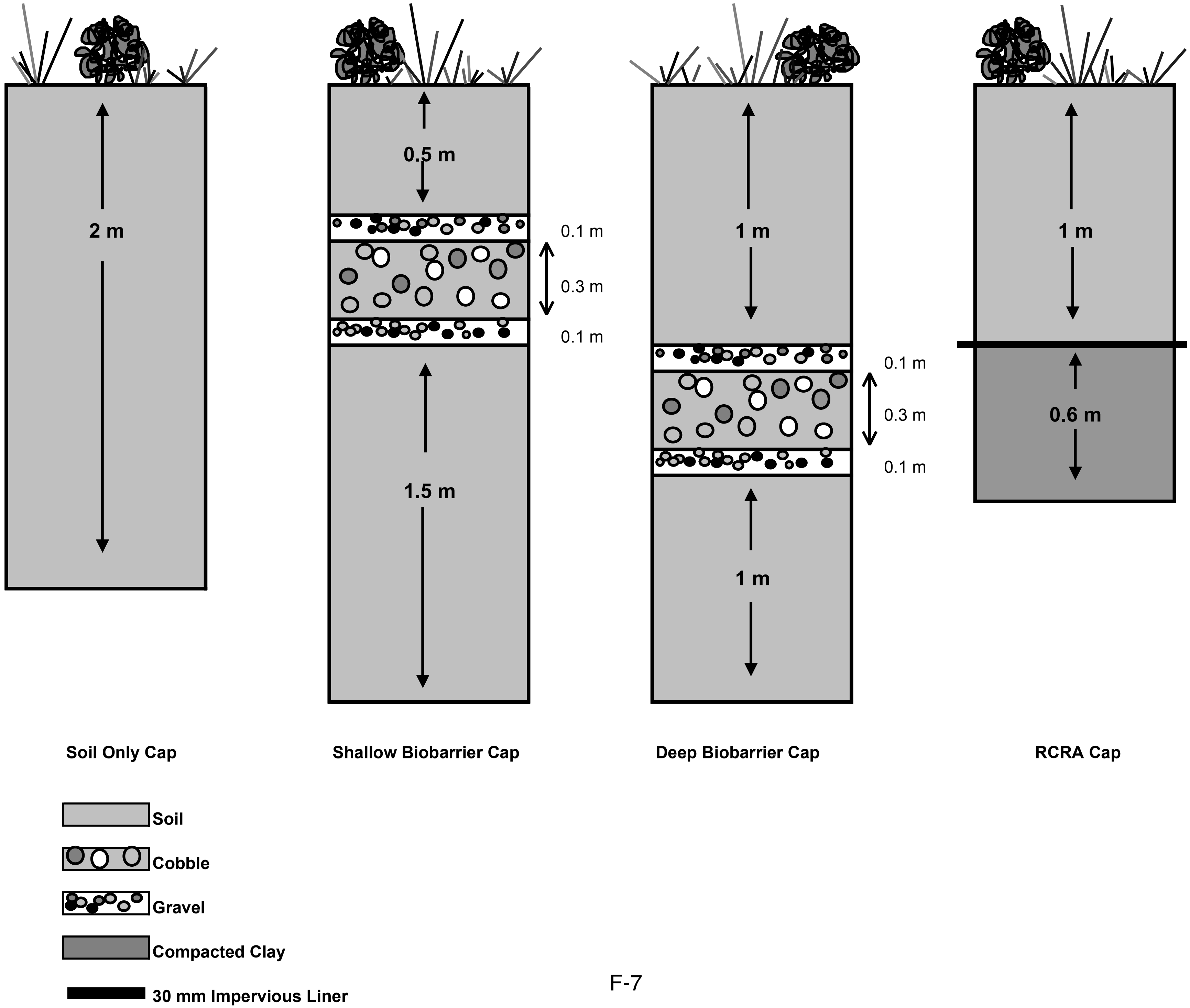

2 m
0.5 m
0.1 m
0.3 m
0.1 m
1.5 m
1 m
0.1 m
0.3 m
0.1 m
1 m
1 m
0.6 m
Soil Only Cap
Shallow Biobarrier Cap
Deep Biobarrier Cap
RCRA Cap
Soil
Cobble
Gravel
Compacted Clay
30 mm Impervious Liner

Figure 6. Cumulative precipitation for the seven water-years (October- September) during which the Protective Cap/Biobarrier Experiment (PCBE) was conducted. Data are from the Idaho Nuclear Technology and Engineering Center (INTEC), the NOAA weather station closest to the PCBE site (4 km south) or from the PCBE site when available.

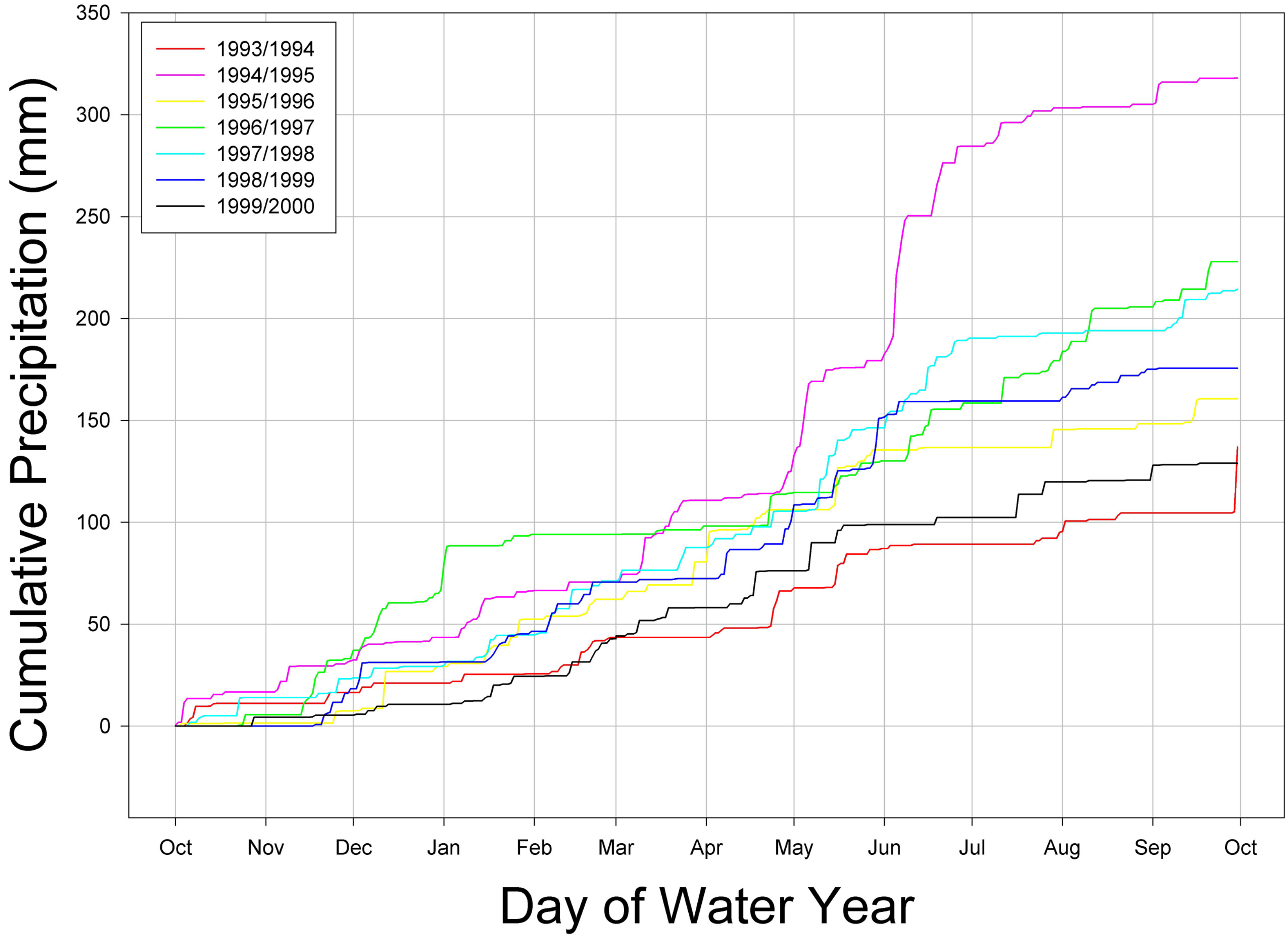
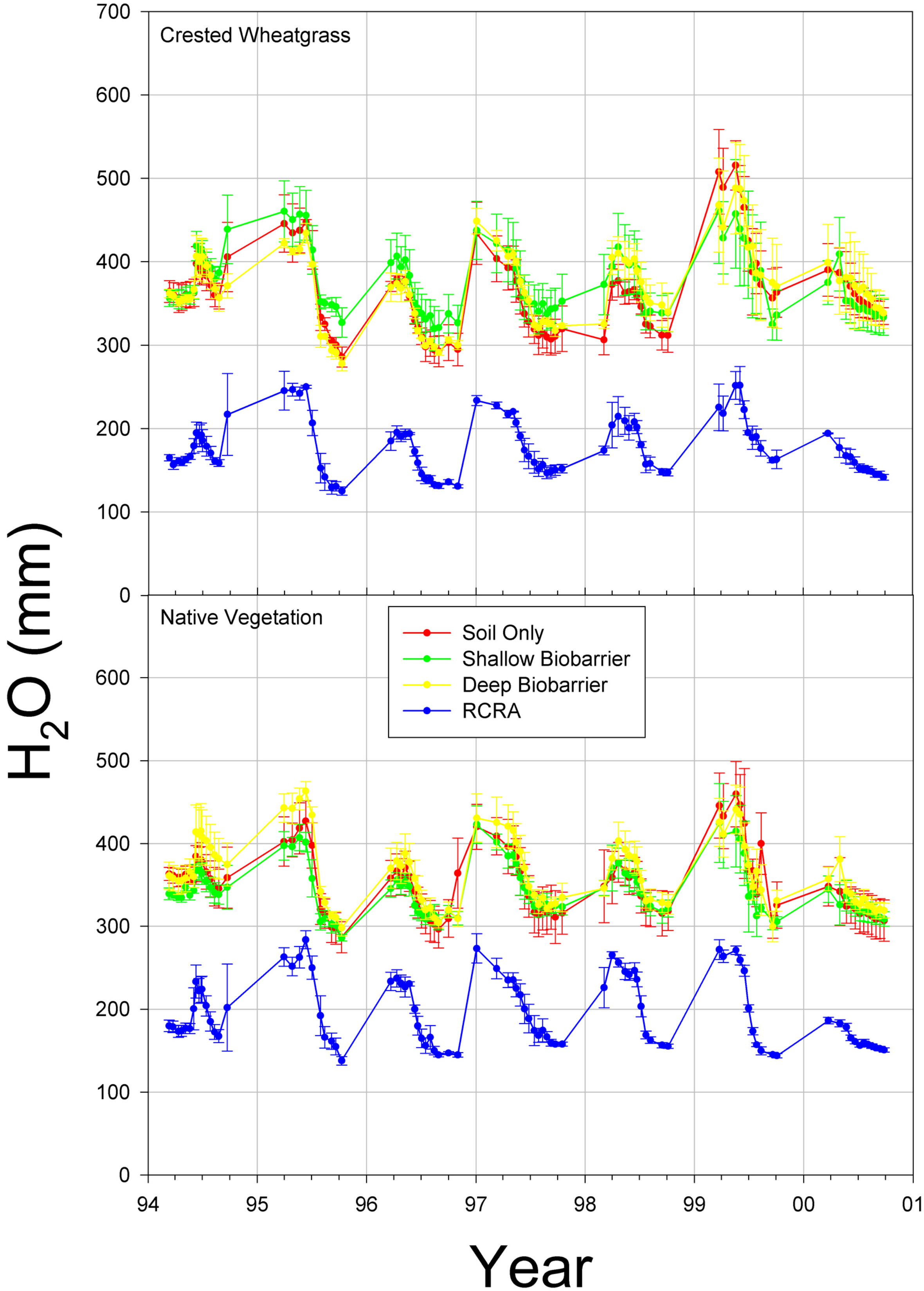
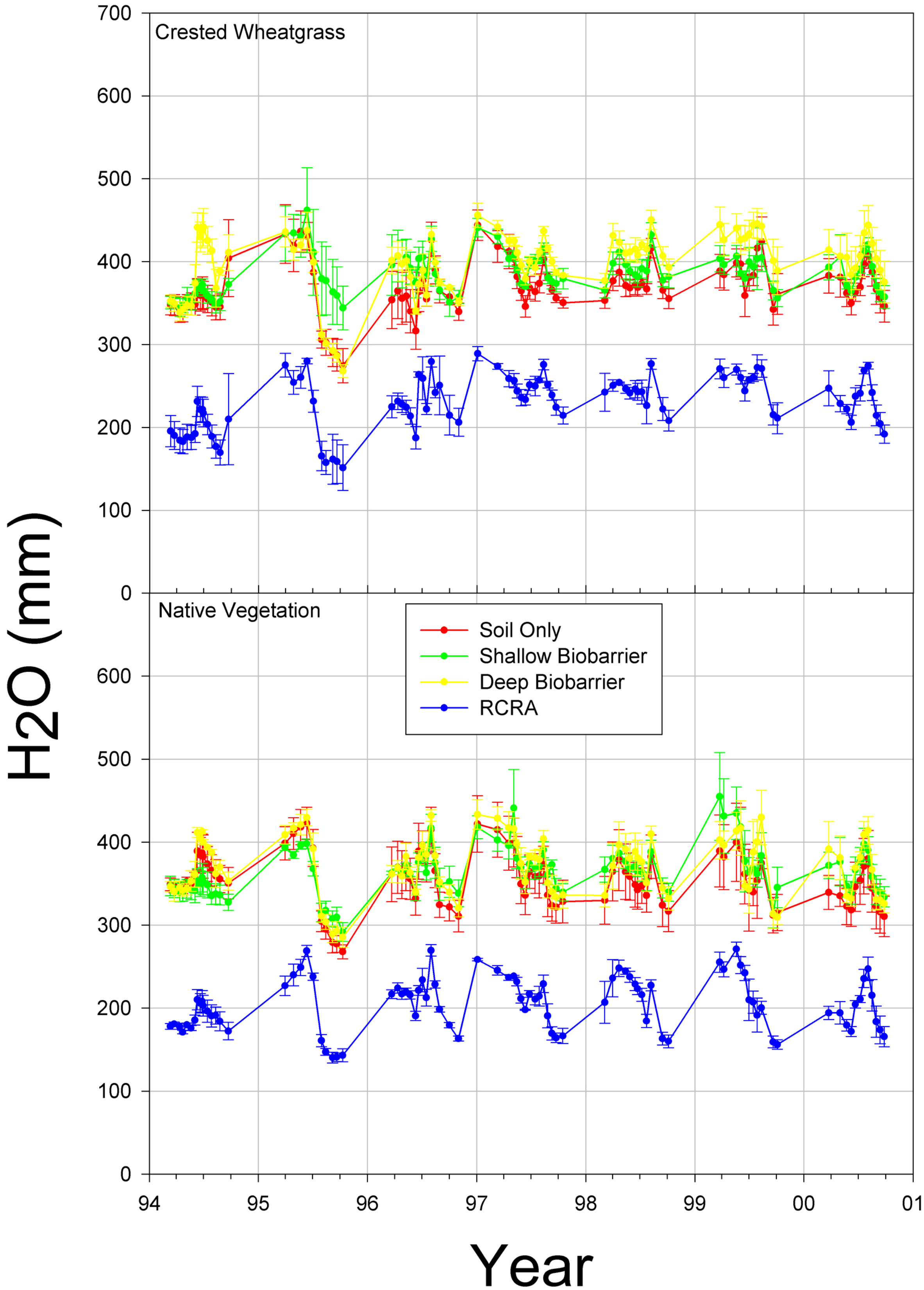

1993/1994
1994/1995
1995/1996
1996/1997
1997/1998
1998/1999
1999/2000
Cumulative Precipitation (mm)
350
300
250
200
150
100
50
0
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Day of Water Year

Figure 7A. Soil moisture in the entire soil profile under ambient precipitation for the four cap configurations in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory during seven years of study. Upper panel shows soil moisture dynamics on subplots planted to crested wheatgrass; lower panel shows soil moisture dynamics on subplots planted with native species. Error bars are ± 1 S.E.



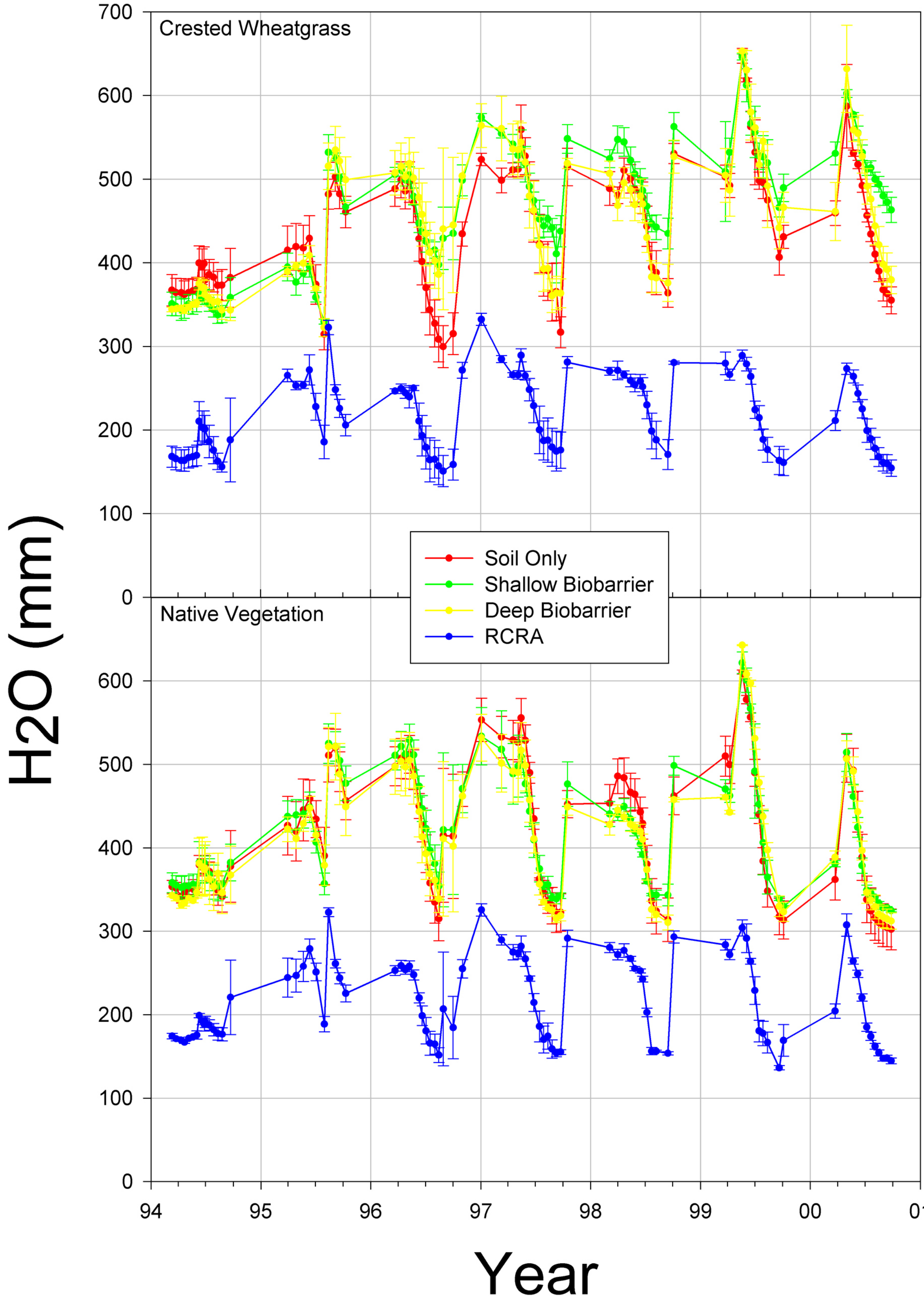
Crested Wheatgrass
Native Vegetation
Soil Only
Shallow Biobarrier
Deep Biobarrier
RCRA
H2O (mm)
Year
700
600
500
400
300
200
100
0
94
95
96
97
98
99
00
01

Figure 7B. Soil moisture in the entire soil profile under summer irrigation for the four cap configurations in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory during seven years of study. Upper panel shows soil moisture dynamics on subplots planted to crested wheatgrass; lower panel shows soil moisture dynamics on subplots planted with native species. Error bars are ± 1 S.E.



Crested Wheatgrass
Native Vegetation
Soil Only
Shallow Biobarrier
Deep Biobarrier
RCRA
H2O (mm)
Year
700
600
500
400
300
200
100
0
94
95
96
97
98
99
00
01

Figure 7C. Soil moisture in the entire soil profile under fall/spring irrigation for the four cap configurations in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory during seven years of study. Upper panel shows soil moisture dynamics on subplots planted to crested wheatgrass; lower panel shows soil moisture dynamics on subplots planted with native species. Error bars are ± 1 S.E.



Crested Wheatgrass
Native Vegetation
Soil Only
Shallow Biobarrier
Deep Biobarrier
RCRA
H2O (mm)
Year
0
100
200
300
400
500
600
700
94
95
96
97
98
99
00
01

Figure 8. Total plant cover on native-vegetation subplots receiving ambient precipitation, summer irrigation, or fall/spring irrigation for the four cap configurations in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory during six years of study. Error bars are ± 1 S.E.

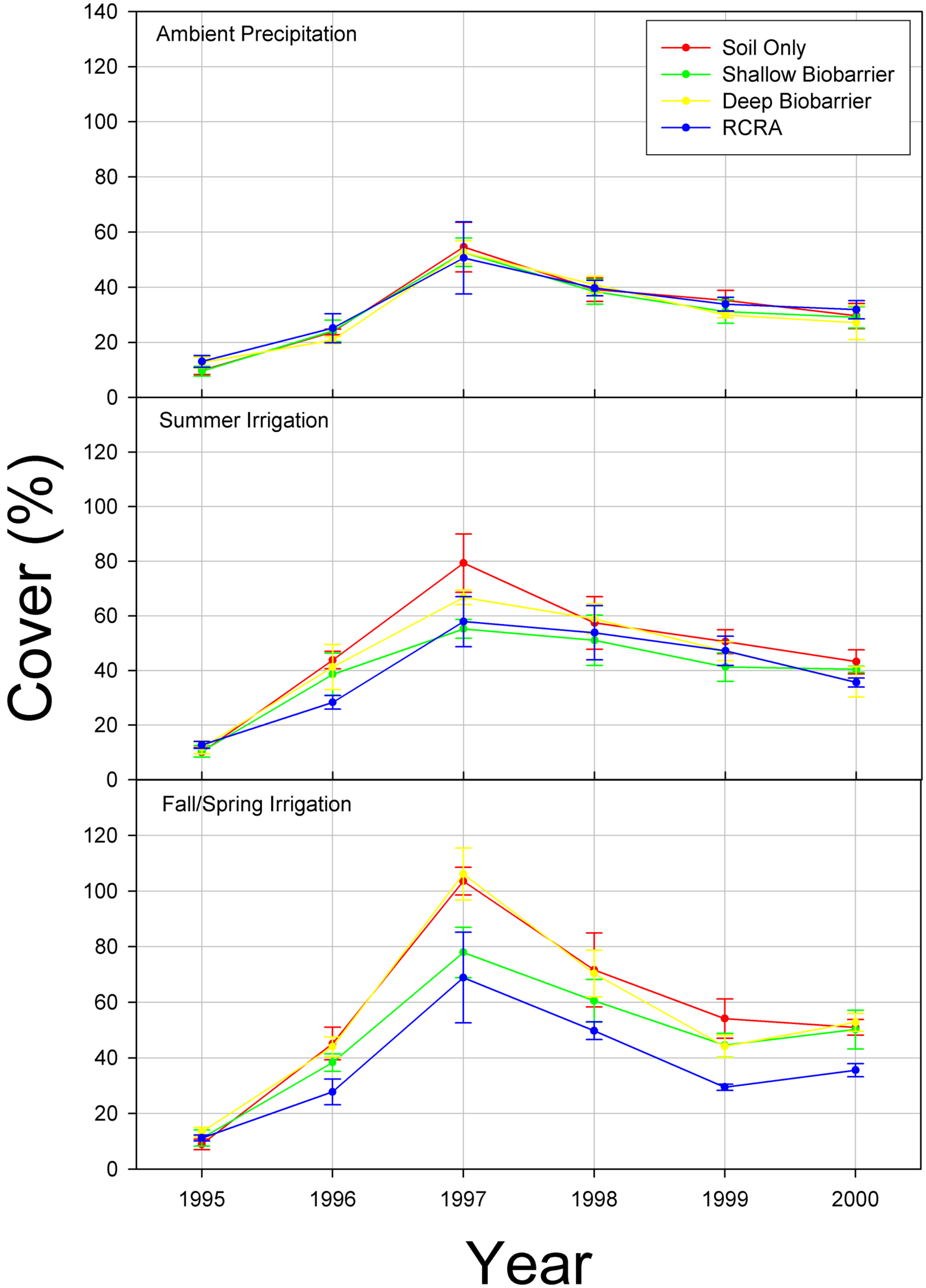
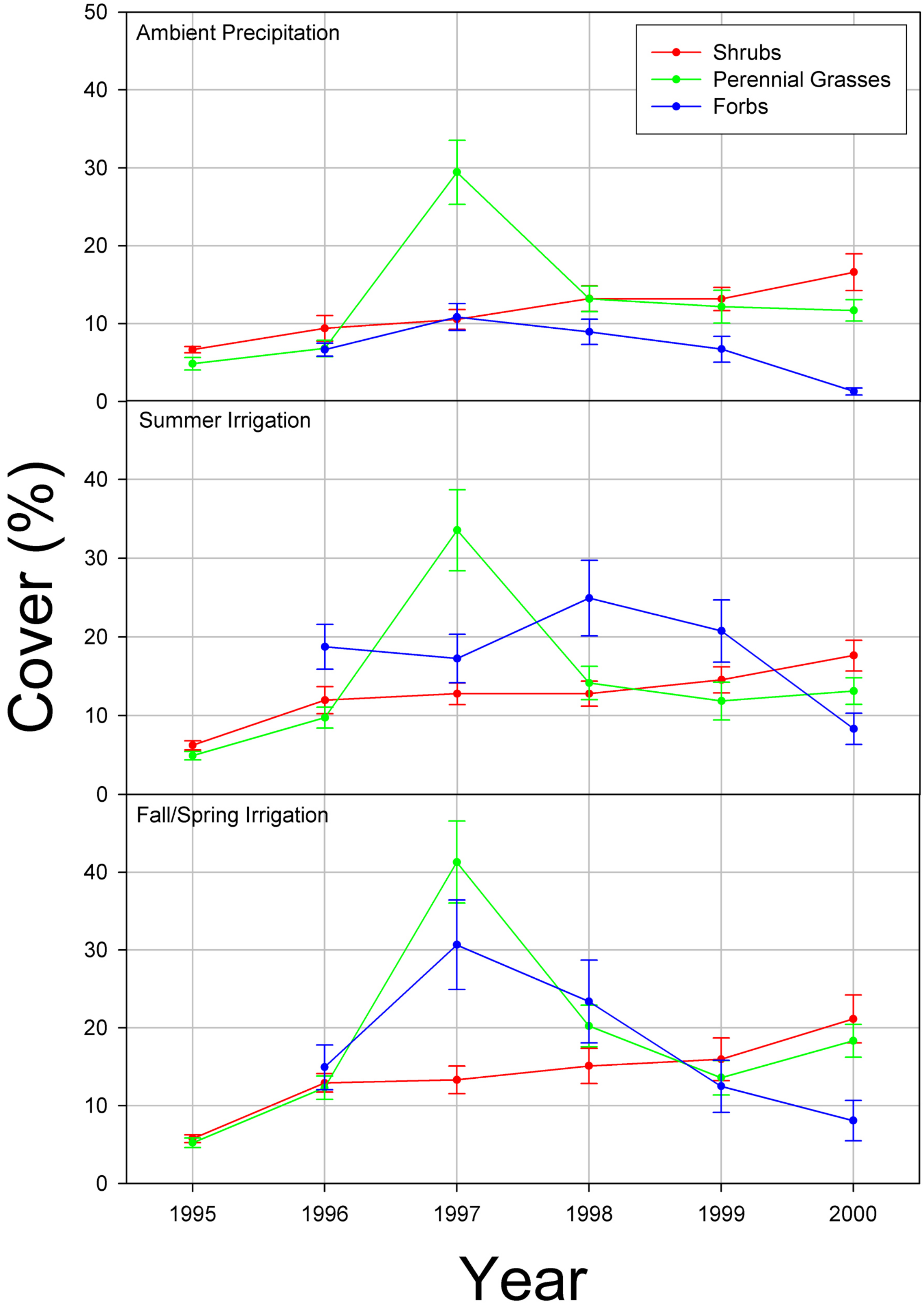

Ambient Precipitation
Soil Only
Shallow Biobarrier
Deep Biobarrier
RCRA
Summer Irrigation
Fall/Spring Irrigation
Cover (%)
Year
0
20
40
60
80
100
120
140
1995
1996
1997
1998
1999
2000

Figure 9. Mean cover of shrubs, perennial grasses, and forbs on plots receiving ambient precipitation, summer irrigation, or fall/spring irrigation in the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory during six years of study. Data were pooled for all four cap configurations. Error bars are ± 1 S.E.



Ambient Precipitation
Shrubs
Perennial Grasses
Forbs
Summer Irrigation
Fall/Spring Irrigation
Cover (%)
Year
0
10
20
30
40
50
1995
1996
1997
1998
1999
2000

Figure 10. Soil moisture profiles for a native-vegetation/soil-only cap receiving ambient precipitation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 5-3 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions.

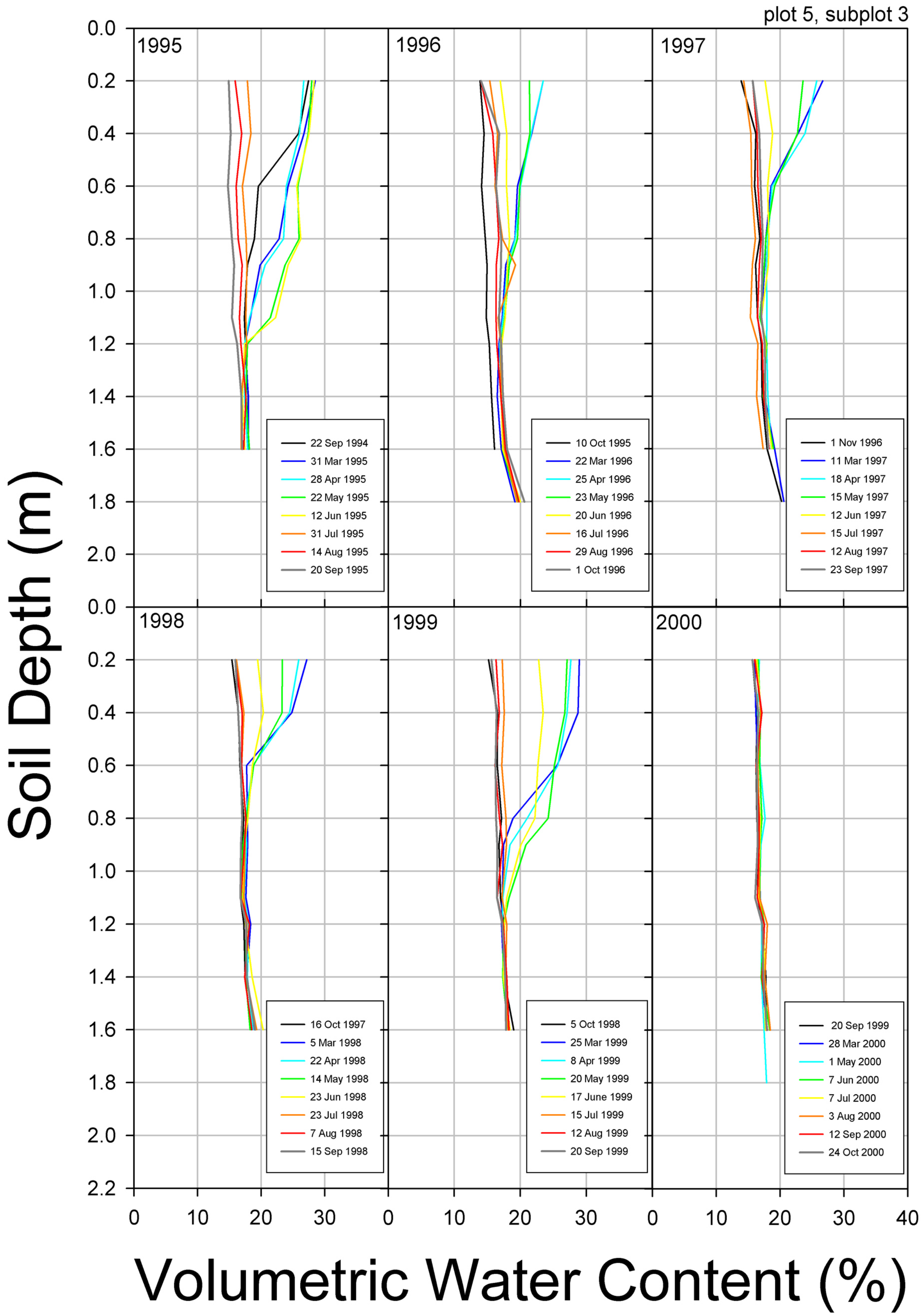

plot 5, subplot 3
1995
1996
1997
1998
1999
2000
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000
Soil Depth (m)
Volumetric Water Content (%)

Figure 11. Soil moisture profiles for a native-vegetation/shallow-biobarrier cap receiving ambient precipitation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 8-3 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions.

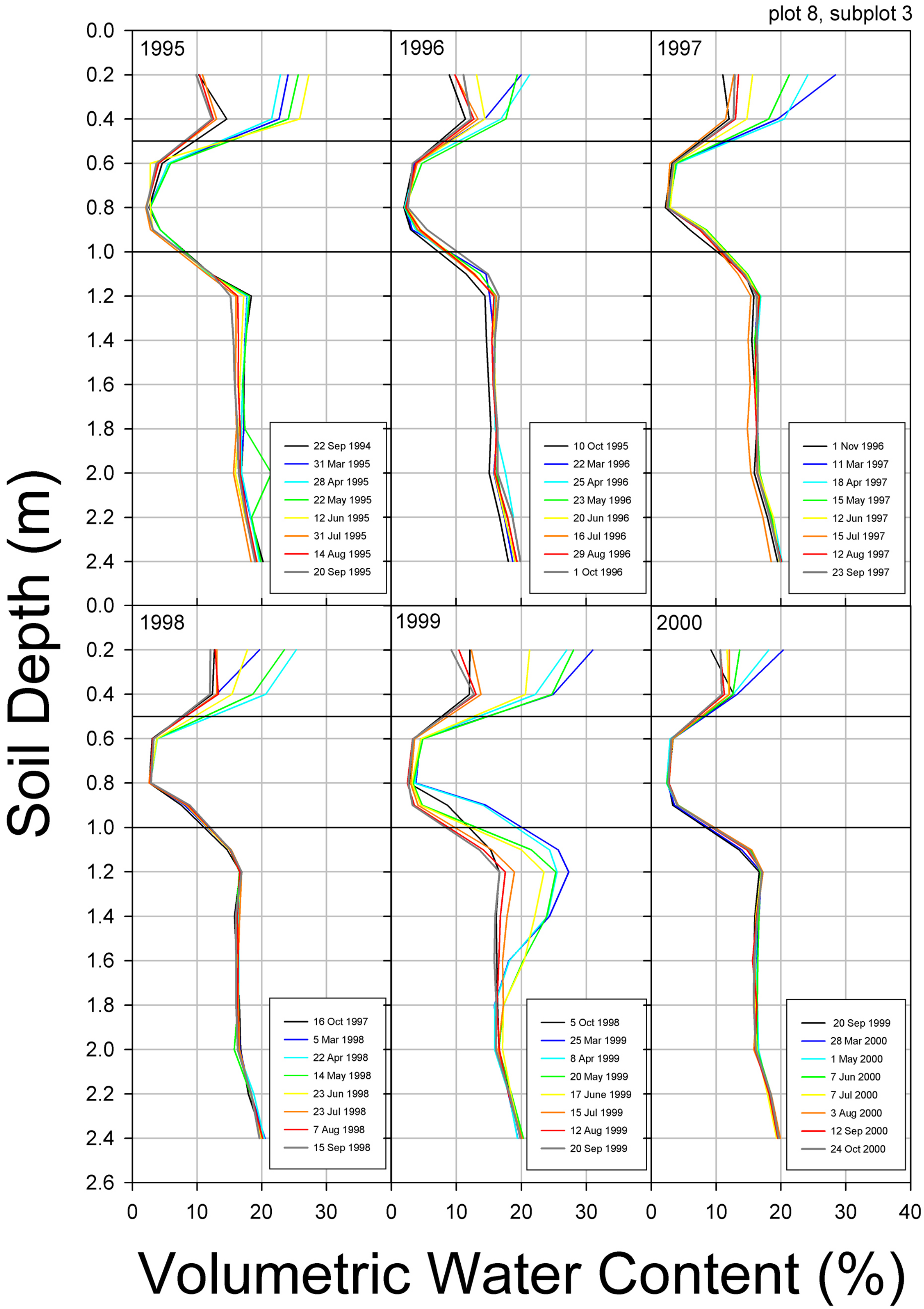

plot 8, subplot 3
1995
1996
1997
1998
1999
2000
Soil Depth (m)
Volumetric Water Content (%)
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000

Figure 12. Soil moisture profiles for a native-vegetation/deep-biobarrier cap receiving ambient precipitation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 9-5 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions.

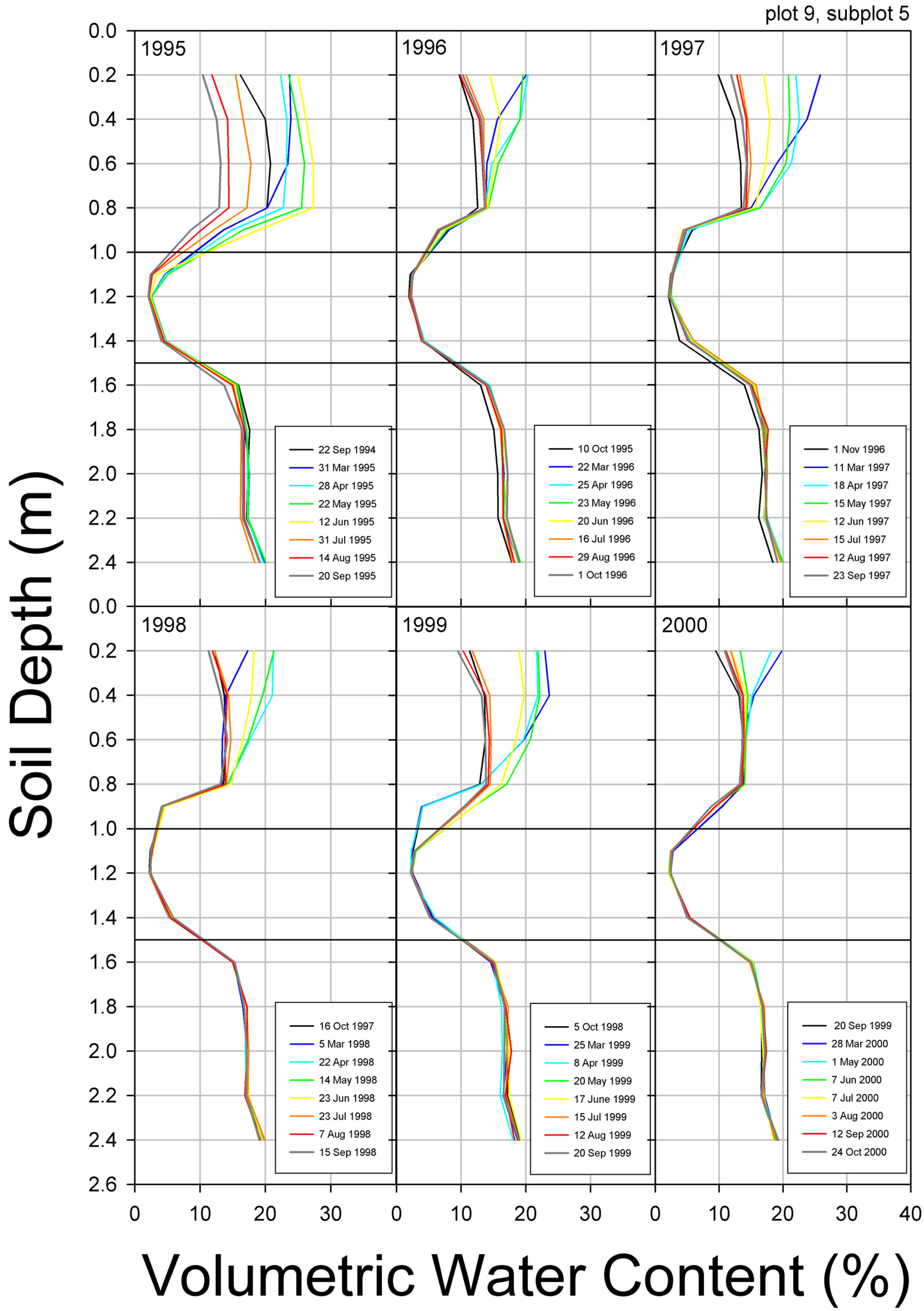
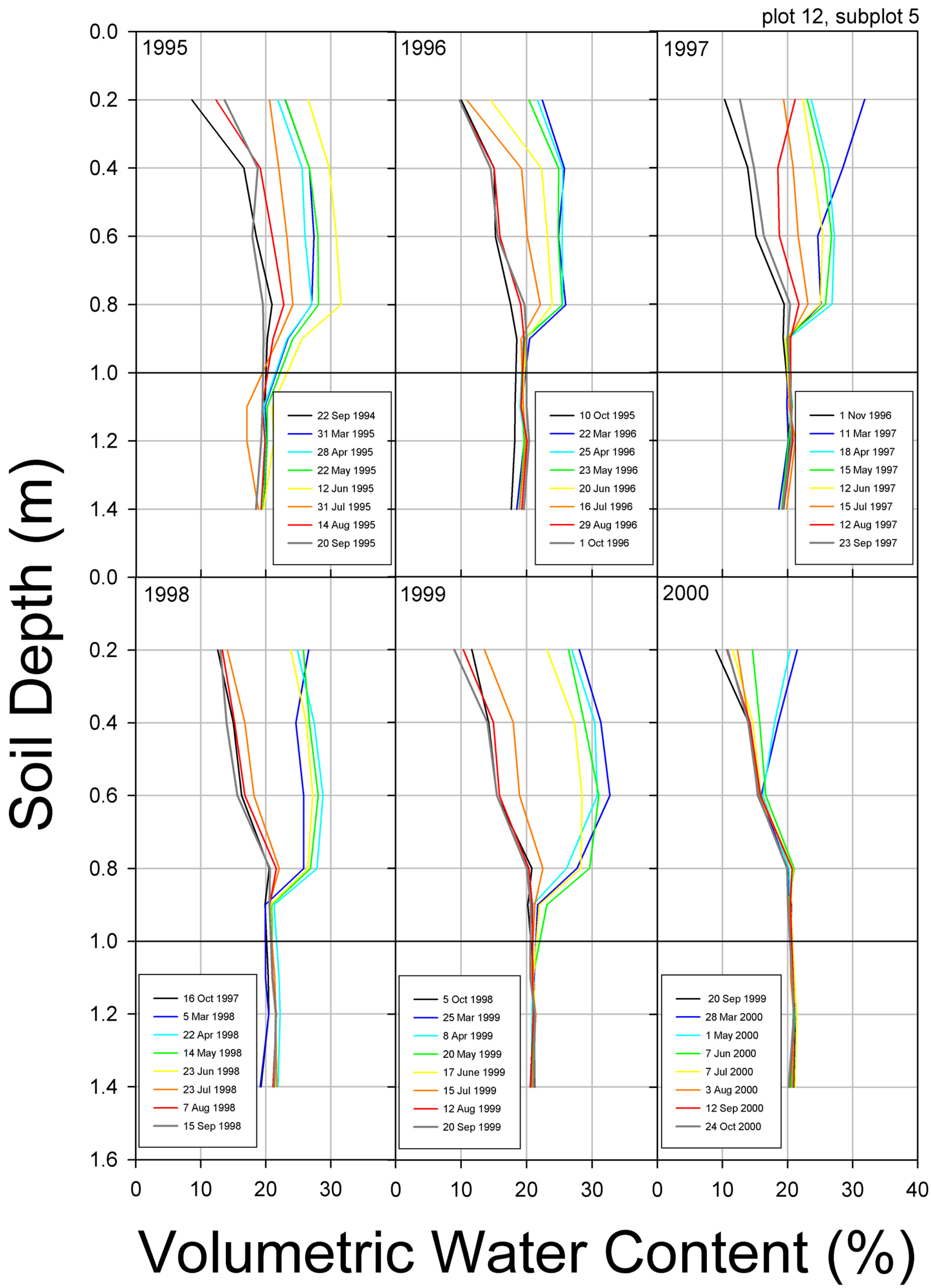
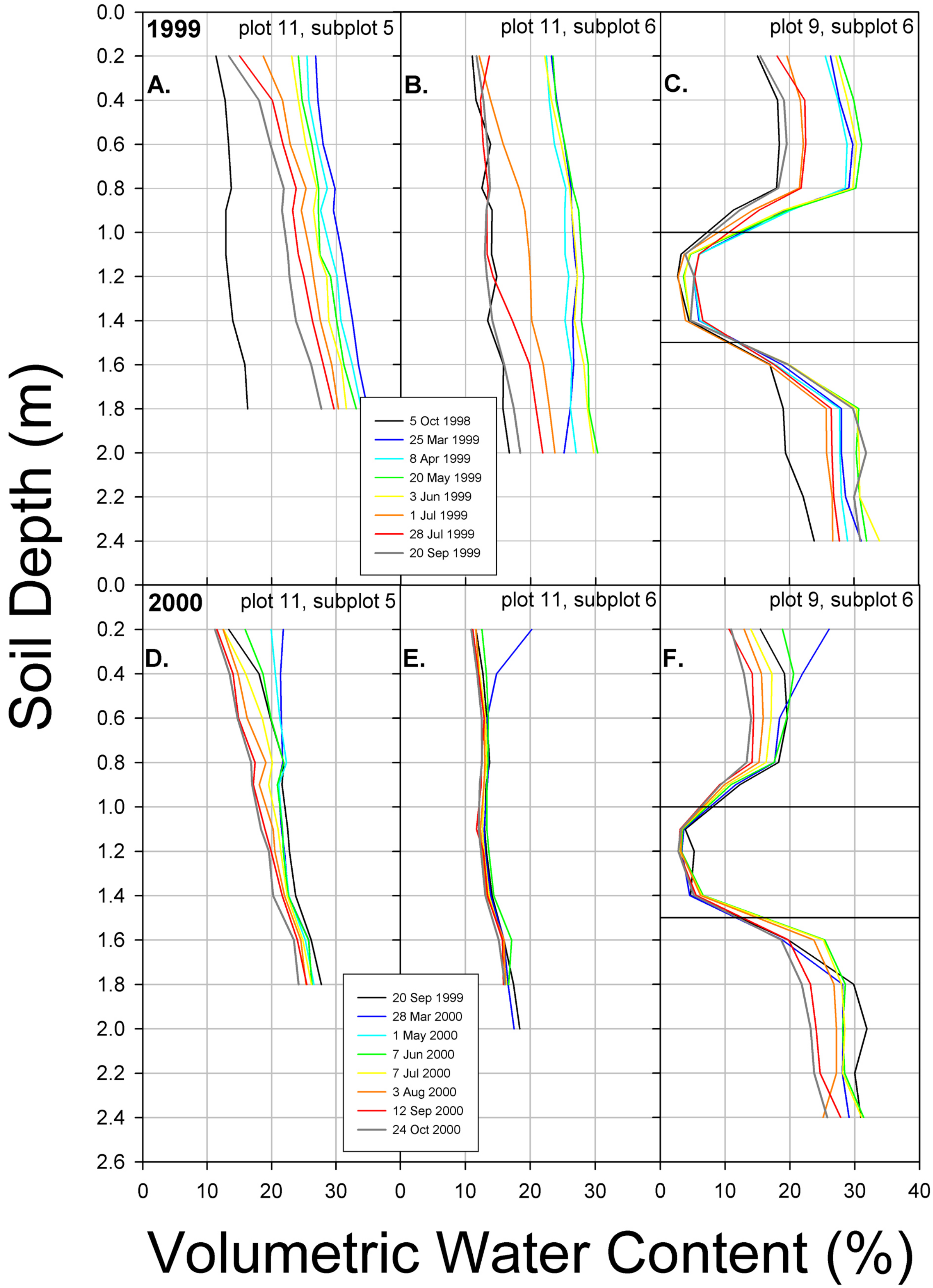

plot 9, subplot 5
1995
1996
1997
1998
1999
2000
Soil Depth (m)
Volumetric Water Content (%)
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000

Figure 13. Soil moisture profiles for a native-vegetation/RCRA cap receiving ambient precipitation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 12-5 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions.



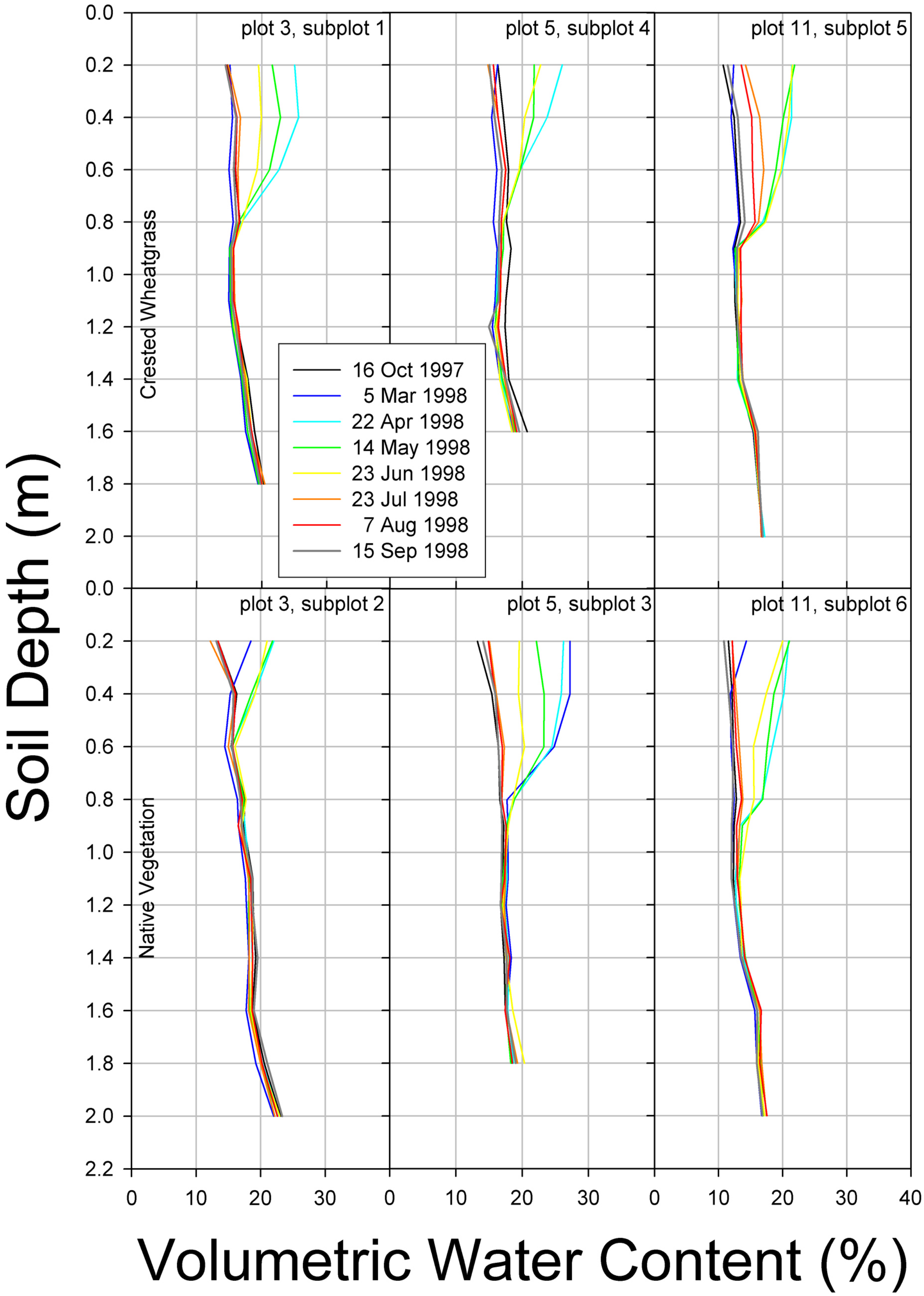
plot 12, subplot 5
1995
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
1996
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1997
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
1998
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
1999
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
2000
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000
Soil Depth (m)
Volumetric Water Content (%)

Figure 14. Soil moisture profiles for 1999 and 2000 of two soil-only and one deep-biobarrier subplots that were flooded by runoff from adjacent areas during snowmelt in March, 1999. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Crested wheatgrass was present on Plot 11-5 and Plot 9-6; native vegetation was present on Plot 11-6.



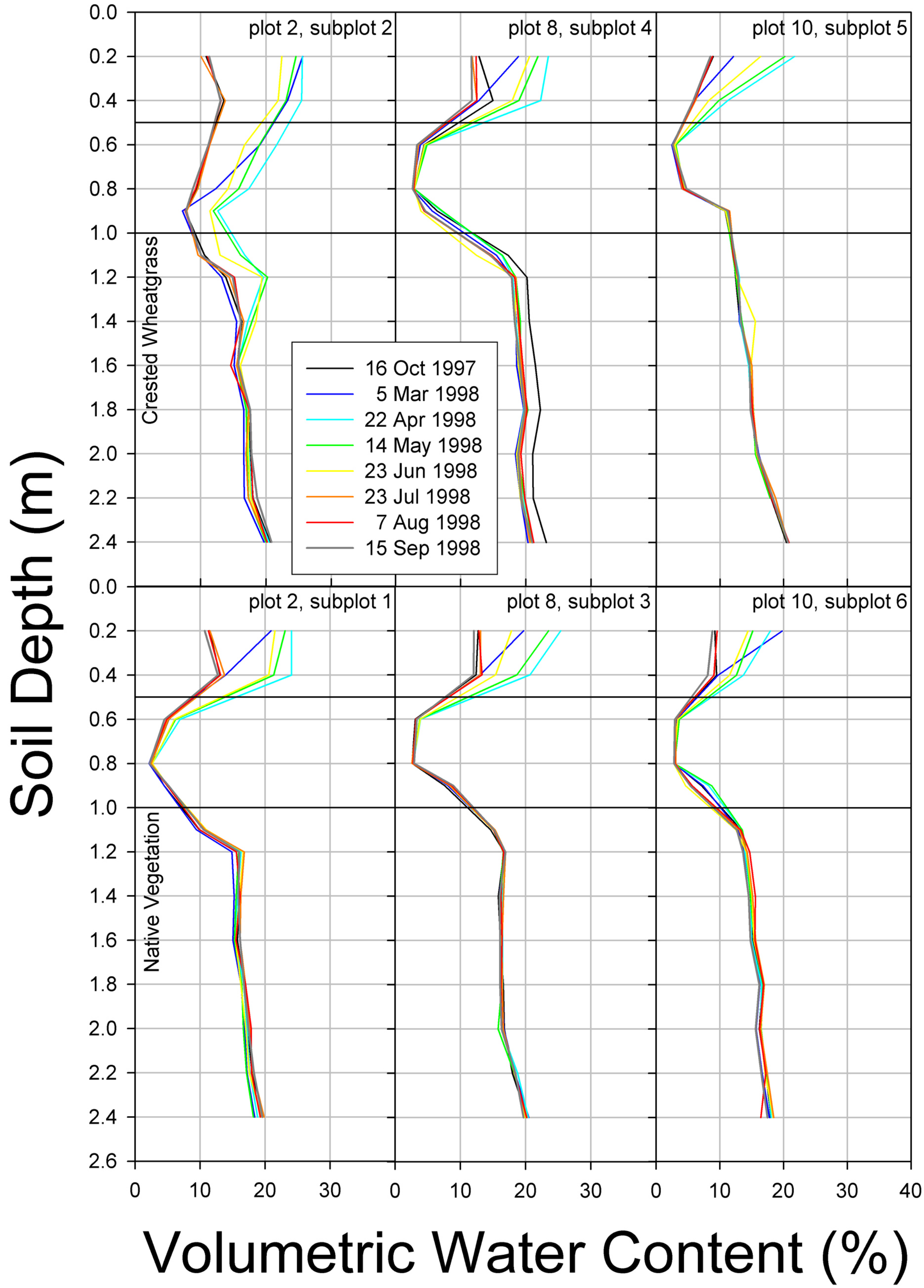
Soil Depth (m)
Volumetric Water Content (%)
1999
plot 11, subplot 5
A.
plot 11, subplot 6
B.
plot 9, subplot 6
C.
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
3 Jun 1999
1 Jul 1999
28 Jul 1999
20 Sep 1999
2000
plot 11, subplot 5
D.
plot 11, subplot 6
E.
plot 9, subplot 6
F.
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000

Figure 15. Soil moisture profiles in 1998 for all soil-only subplots receiving ambient precipitation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.



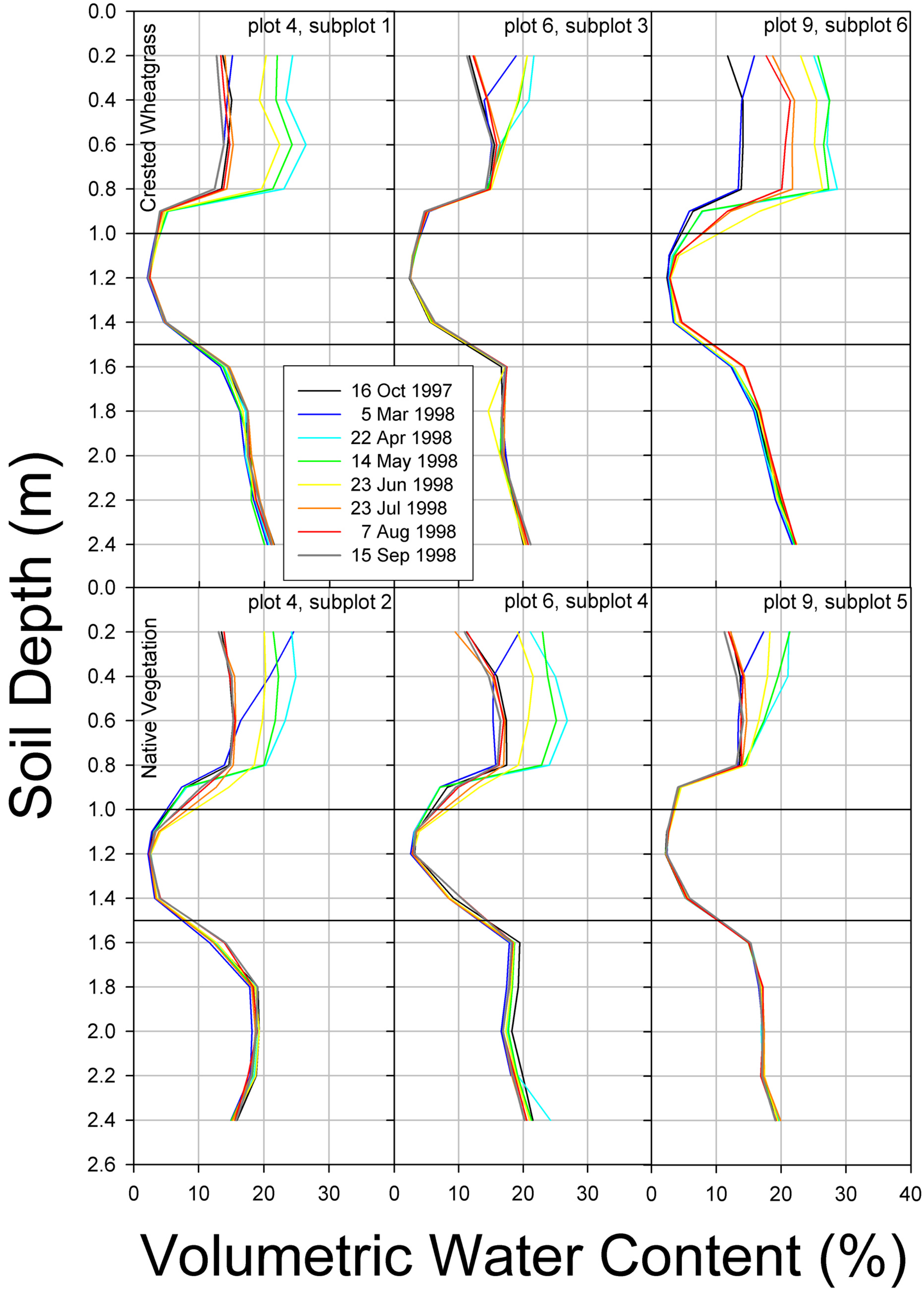
plot 3, subplot 1
plot 5, subplot 4
plot 11, subplot 5
plot 3, subplot 2
plot 5, subplot 3
plot 11, subplot 6
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 16. Soil moisture profiles in 1998 for all shallow biobarrier subplots receiving ambient precipitation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.



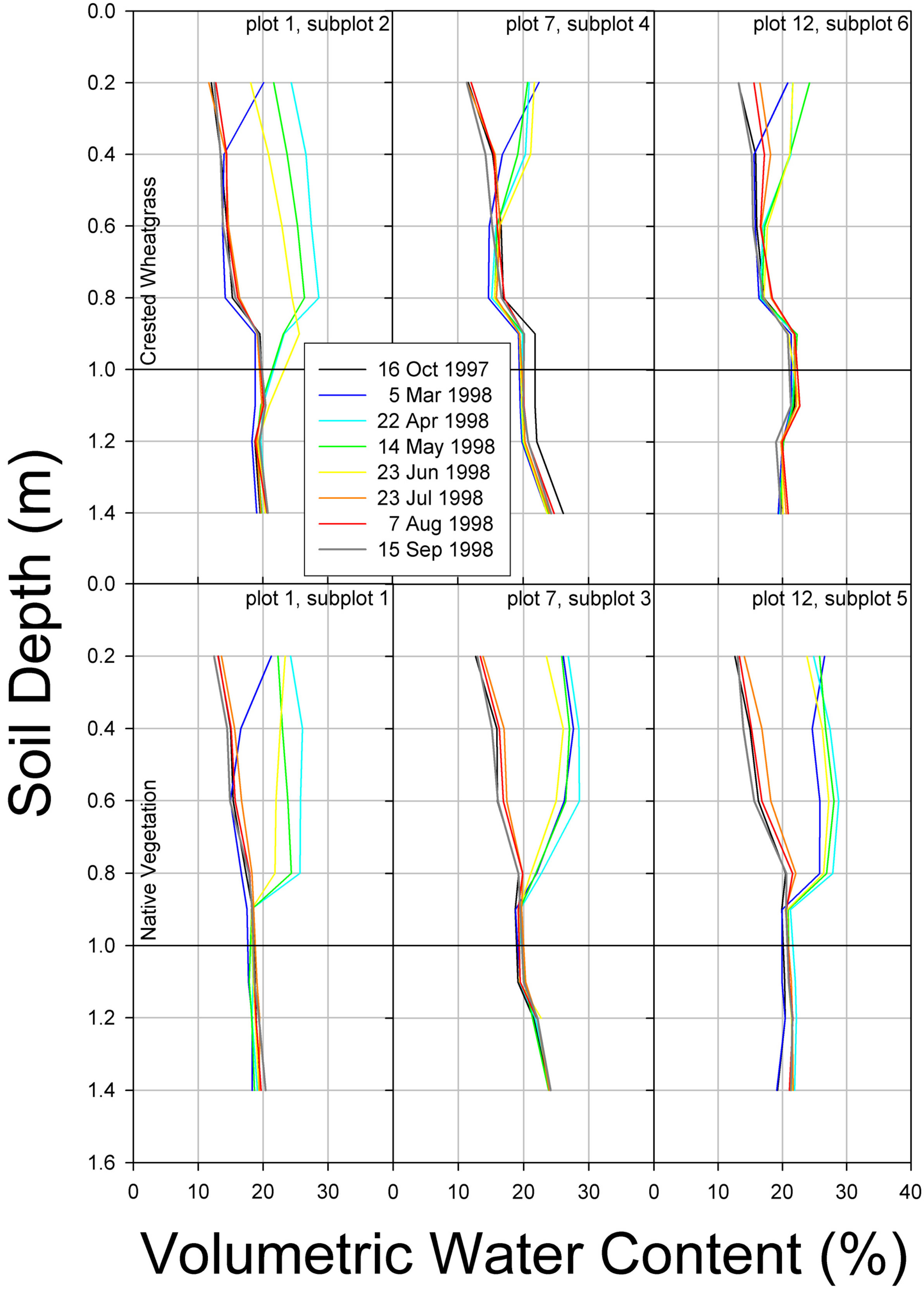
plot 2, subplot 2
plot 8, subplot 4
plot 10, subplot 5
plot 2, subplot 1
plot 8, subplot 3
plot 10, subplot 6
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
0
10
20
30
40

Figure 17. Soil moisture profiles in 1998 for all deep biobarrier subplots receiving ambient precipitation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.



plot 4, subplot 1
plot 6, subplot 3
plot 9, subplot 6
plot 4, subplot 2
plot 6, subplot 4
plot 9, subplot 5
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 18. Soil moisture profiles in 1998 for all RCRA subplots receiving ambient precipitation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.



plot 1, subplot 2
plot 7, subplot 4
plot 12, subplot 6
plot 1, subplot 1
plot 7, subplot 3
plot 12, subplot 5
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 19. Soil moisture profiles for a native-vegetation/soil-only cap receiving summer irrigation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 5-2 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Summer irrigation treatments began in June of 1996, so data for 1995 were taken under ambient precipitation.

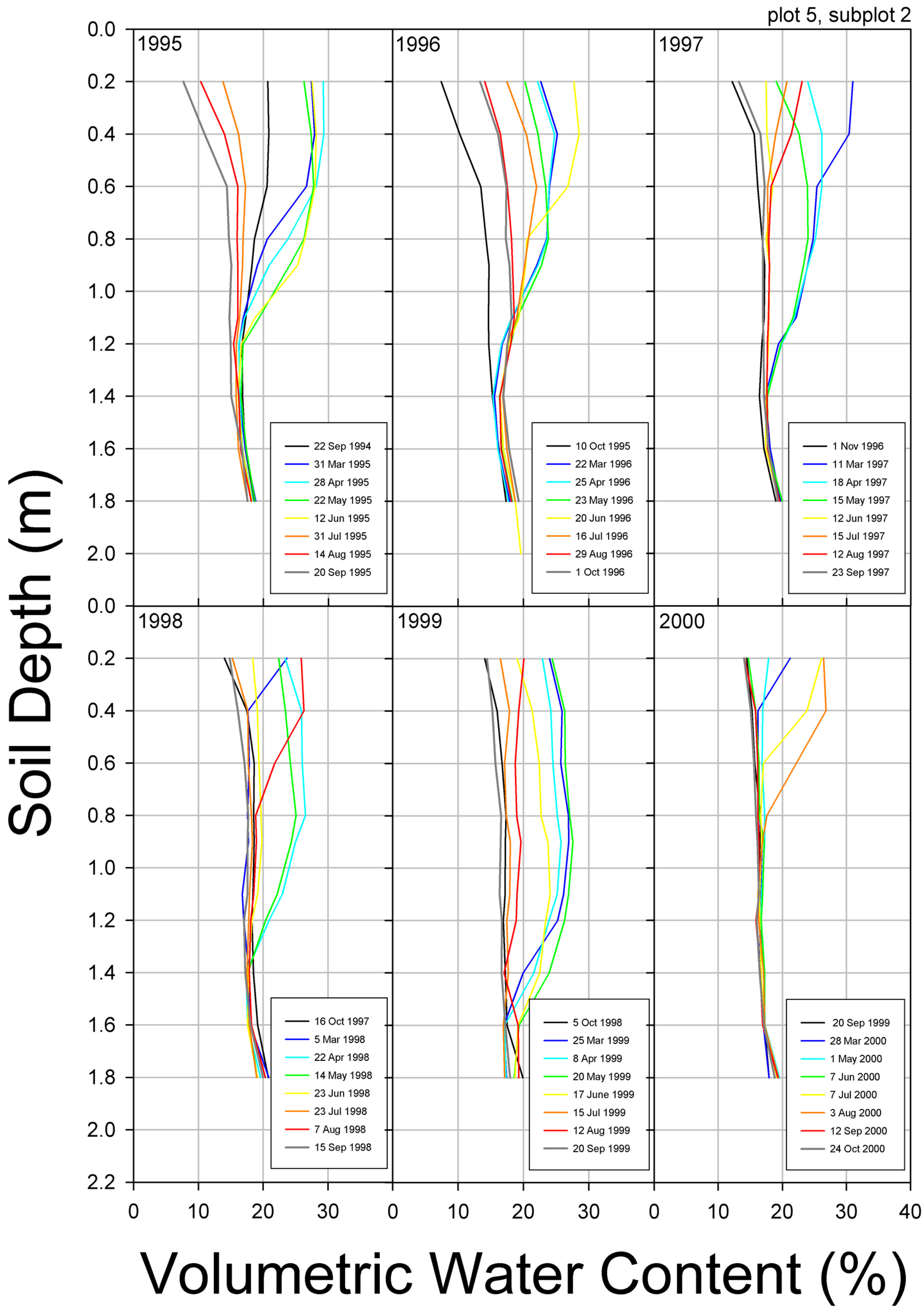
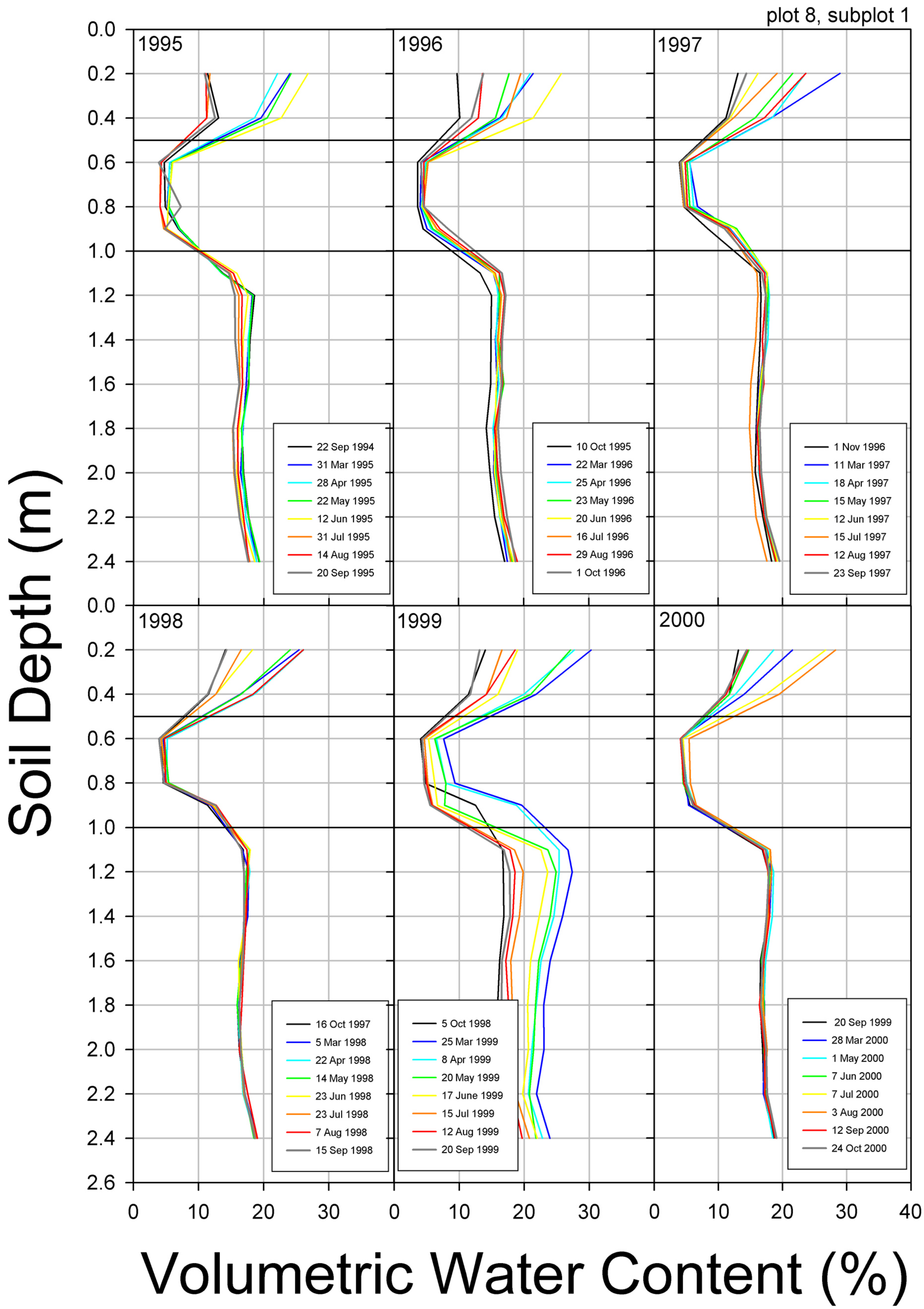

plot 5, subplot 2
1995
1996
1997
1998
1999
2000
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000
Soil Depth (m)
Volumetric Water Content (%)

Figure 20. Soil moisture profiles for a native-vegetation/shallow-biobarrier cap receiving summer irrigation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 8-1 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Summer irrigation treatments began in June of 1996, so data for 1995 were taken under ambient precipitation.



plot 8, subplot 1
1995
1996
1997
1998
1999
2000
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000
Soil Depth (m)
Volumetric Water Content (%)

Figure 21. Soil moisture profiles for a native-vegetation/deep-biobarrier cap receiving summer irrigation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 9-4 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Summer irrigation treatments began in June of 1996, so data for 1995 were taken under ambient precipitation.

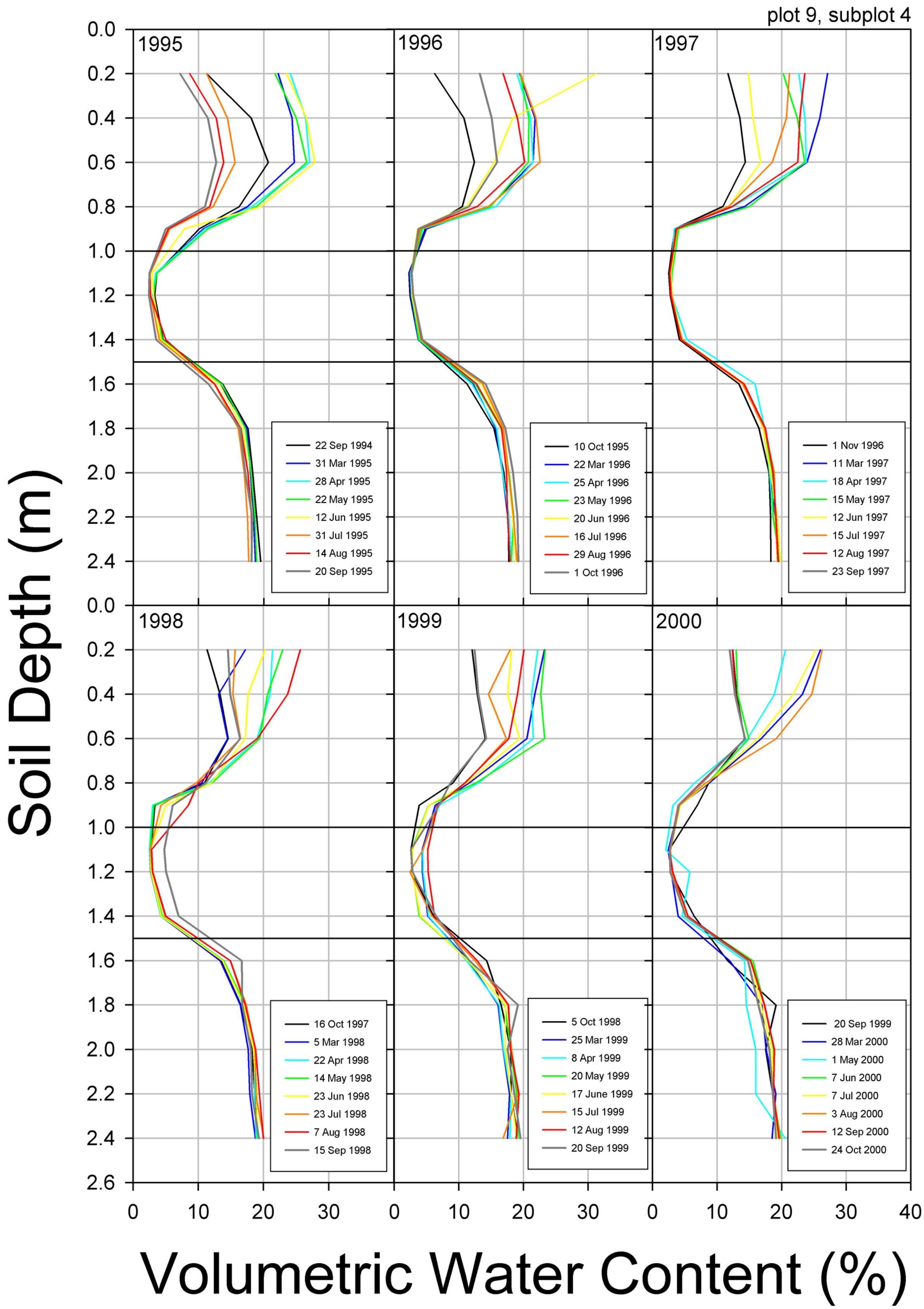

plot 9, subplot 4
1995
1996
1997
1998
1999
2000
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000
Soil Depth (m)
Volumetric Water Content (%)

Figure 22. Soil moisture profiles for a native-vegetation/RCRA cap receiving summer irrigation for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 1-5 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Summer irrigation treatments began in June of 1996, so data for 1995 were taken under ambient precipitation.

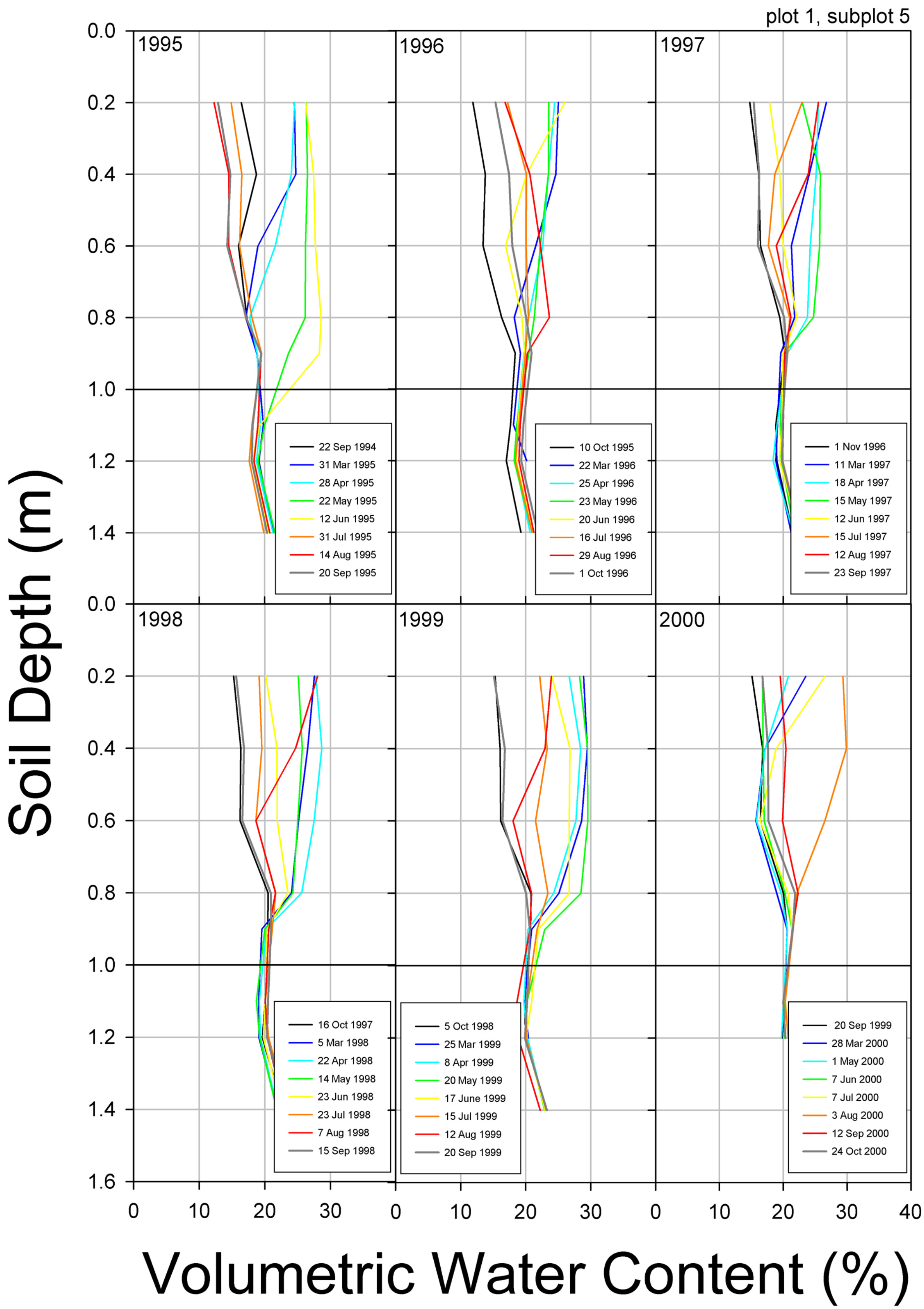

plot 1, subplot 5
1995
1996
1997
1998
1999
2000
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000
Soil Depth (m)
Volumetric Water Content (%)

Figure 23. Soil moisture profiles in 1998 for all soil-only subplots receiving summer irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.

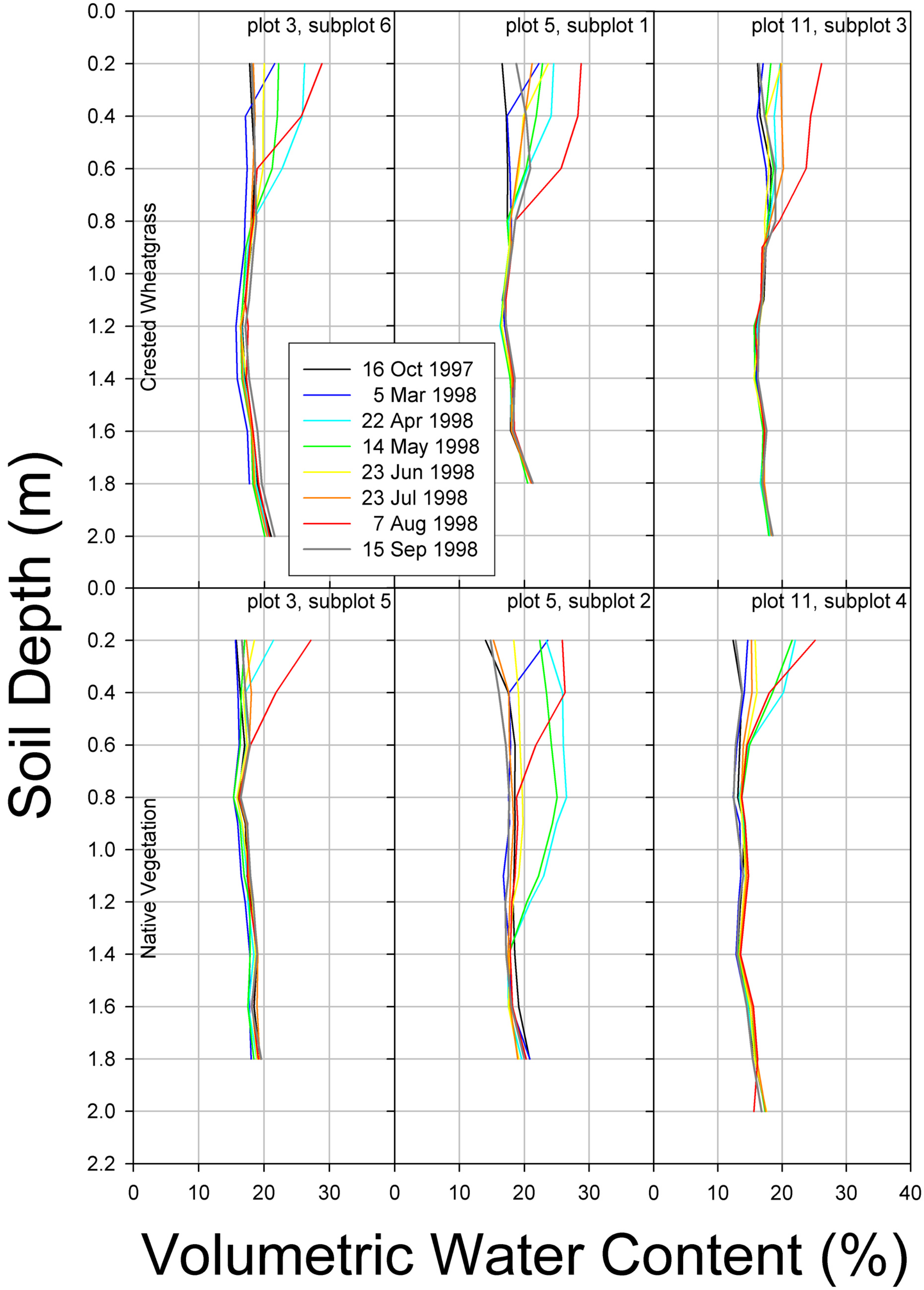

plot 3, subplot 6
plot 5, subplot 1
plot 11, subplot 3
plot 3, subplot 5
plot 5, subplot 2
plot 11, subplot 4
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 24. Soil moisture profiles in 1998 for all shallow-biobarrier subplots receiving summer irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.

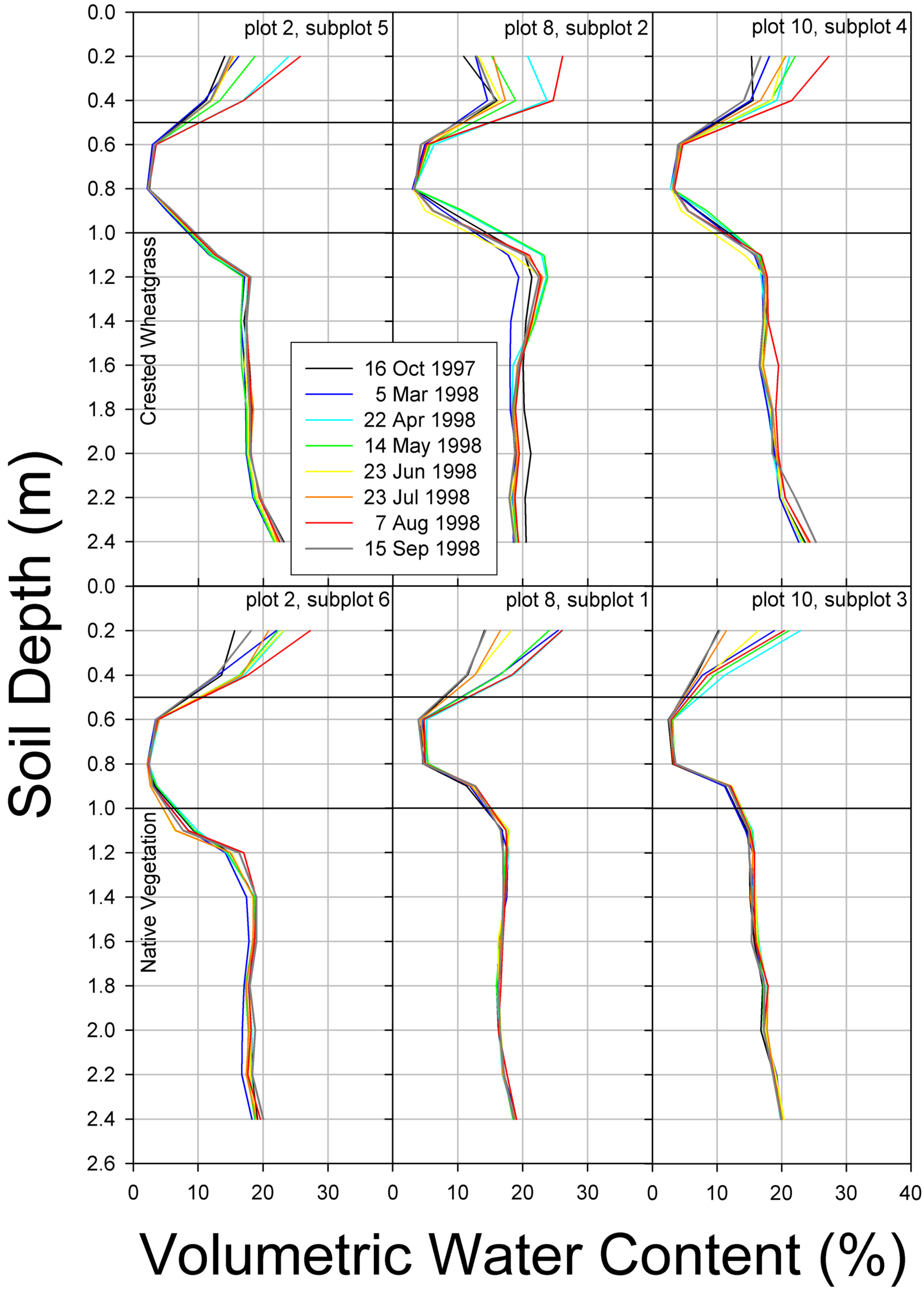
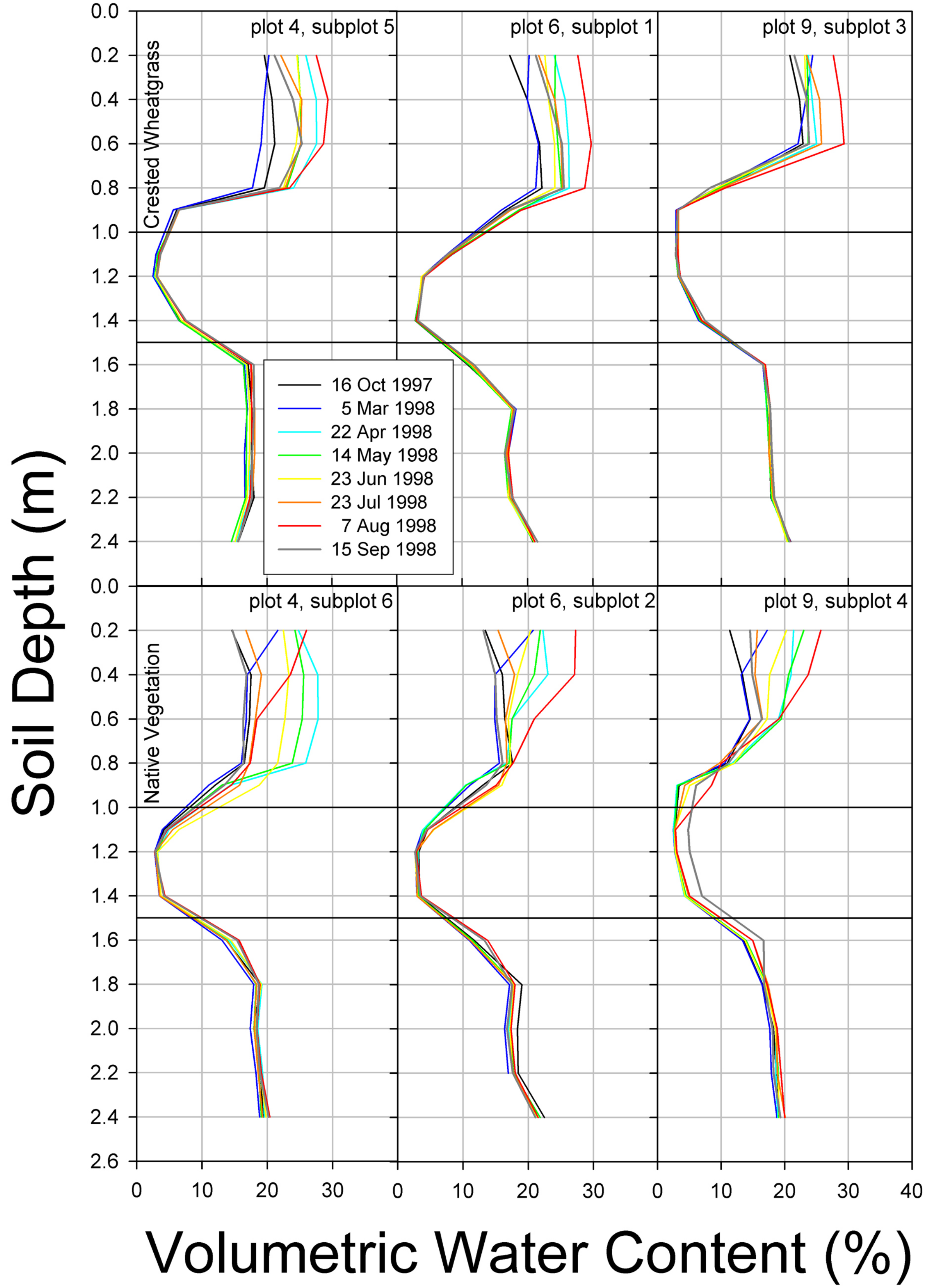
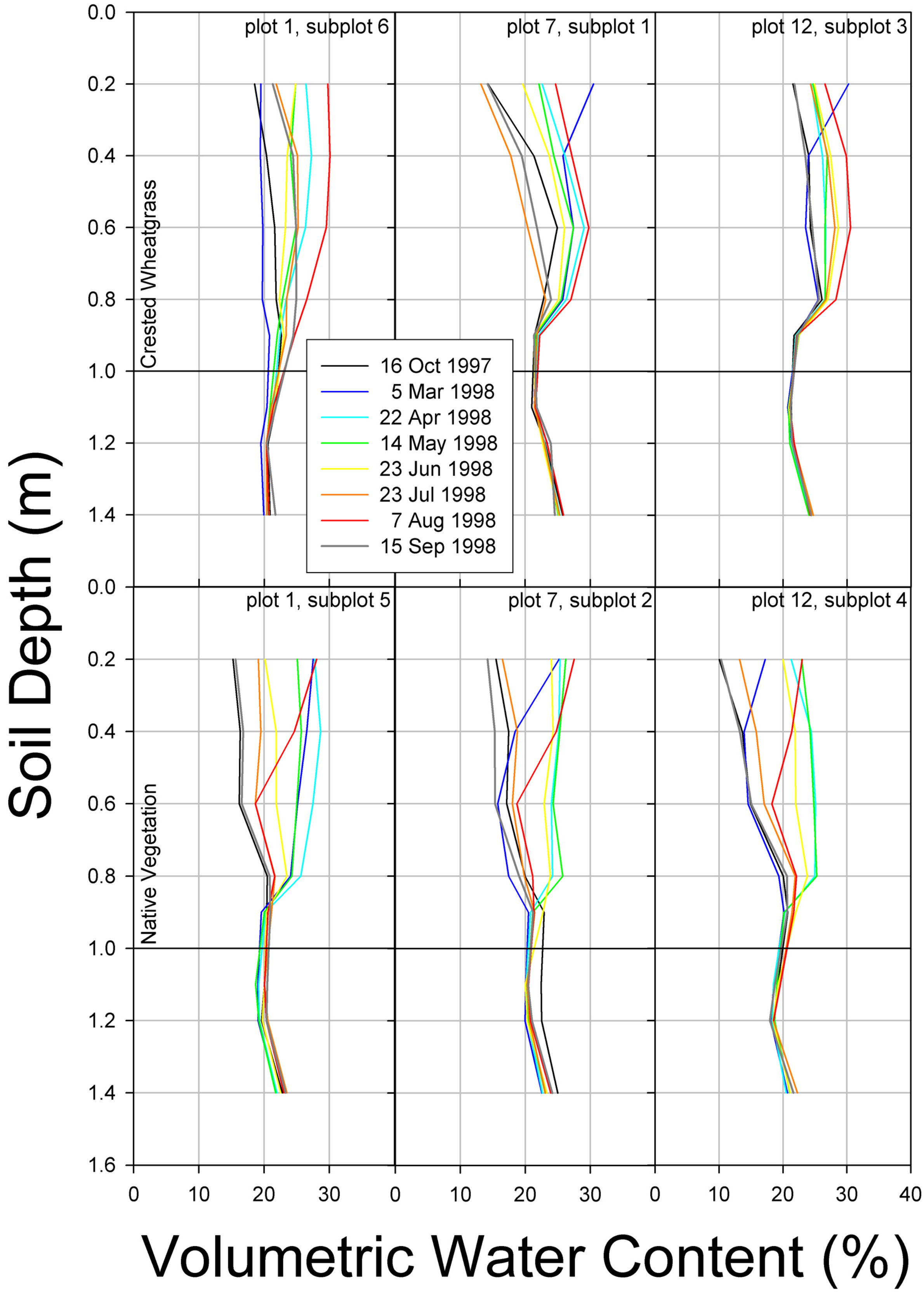

plot 2, subplot 5
plot 8, subplot 2
plot 10, subplot 4
plot 2, subplot 6
plot 8, subplot 1
plot 10, subplot 3
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 25. Soil moisture profiles in 1998 for all deep-biobarrier subplots receiving summer irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.



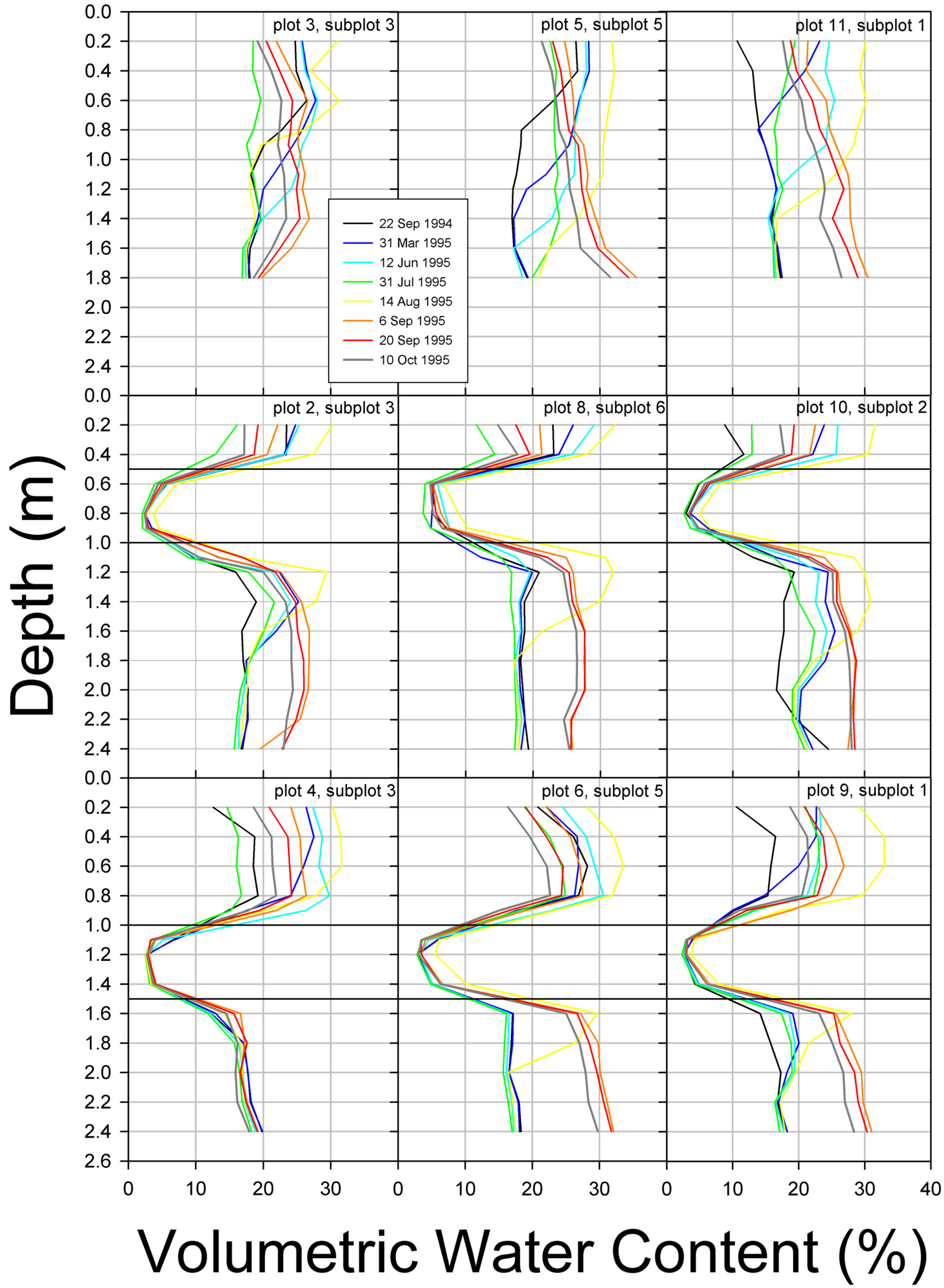
plot 4, subplot 5
plot 6, subplot 1
plot 9, subplot 3
Crested Wheatgrass
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
plot 4, subplot 6
plot 6, subplot 2
plot 9, subplot 4
Native Vegetation
Soil Depth (m)
Volumetric Water Content (%)

Figure 26. Soil moisture profiles in 1998 for all RCRA subplots receiving summer irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.



plot 1, subplot 6
plot 7, subplot 1
plot 12, subplot 3
plot 1, subplot 5
plot 7, subplot 2
plot 12, subplot 4
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
10
20
30
40

Figure 27A. Soil moisture profiles for all soil-only, shallow-biobarrier, and deep-biobarrier subplots having native vegetation that received 550 mm of irrigation water in early August of 1995. Yellow lines depict soil water content immediately following the irrigation treatment.



plot 3, subplot 3
plot 5, subplot 5
plot 11, subplot 1
plot 2, subplot 3
plot 8, subplot 6
plot 10, subplot 2
plot 4, subplot 3
plot 6, subplot 5
plot 9, subplot 1
22 Sep 1994
31 Mar 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
6 Sep 1995
20 Sep 1995
10 Oct 1995
Depth (m)
Volumetric Water Content (%)

Figure 27B. Soil moisture profiles for all soil-only, shallow-biobarrier, and deep-biobarrier subplots having crested wheatgrass vegetation that received 550 mm of irrigation water in early August of 1995. Yellow lines depict soil water content immediately following the irrigation treatment.

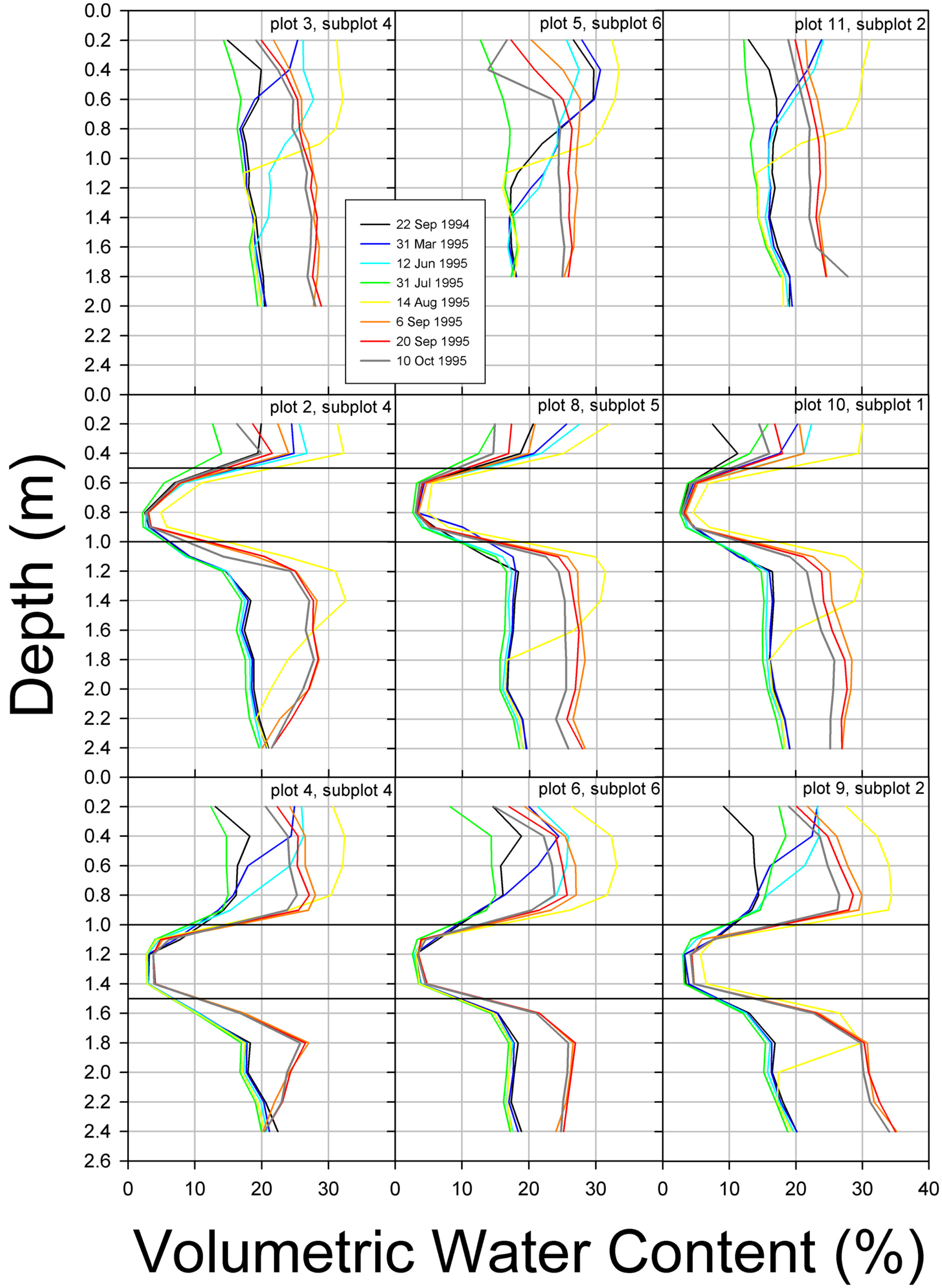

plot 3, subplot 4
plot 5, subplot 6
plot 11, subplot 2
plot 2, subplot 4
plot 8, subplot 5
plot 10, subplot 1
plot 4, subplot 4
plot 6, subplot 6
plot 9, subplot 2
22 Sep 1994
31 Mar 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
6 Sep 1995
20 Sep 1995
10 Oct 1995
Depth (m)
Volumetric Water Content (%)

Figure 28. Soil moisture profiles in 1996 for three of the native-vegetation subplots depicted in Figure 27, which received 550 mm of supplemental irrigation in August, 1995. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.

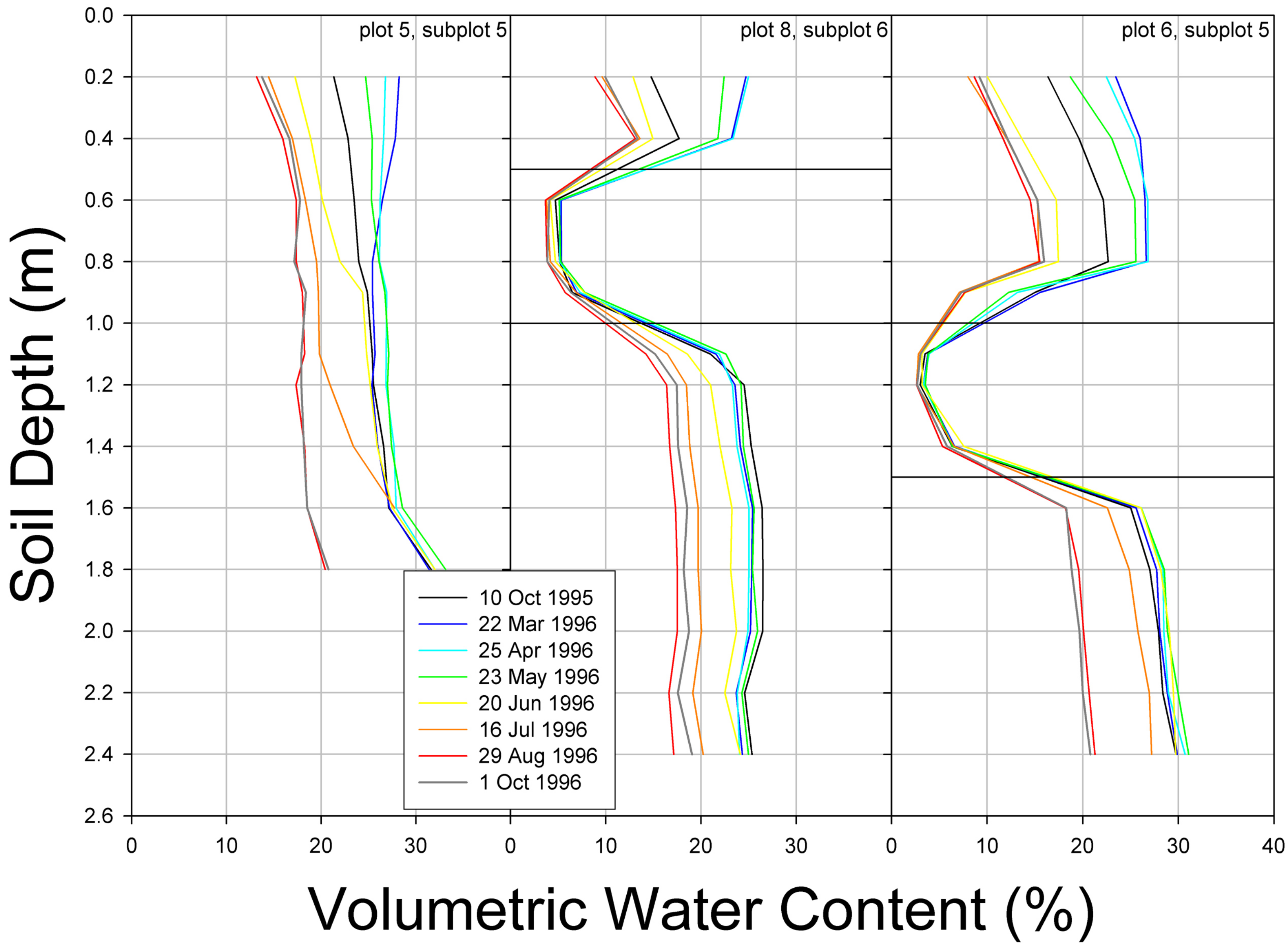

plot 5, subplot 5
plot 8, subplot 6
plot 6, subplot 5
Soil Depth (m)
Volumetric Water Content (%)
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
0
10
20
30
40

Figure 29. Soil moisture profiles for a native-vegetation/soil-only cap receiving fall/spring for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 3-3 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Fall/spring irrigation treatments were initiated in August, 1995.

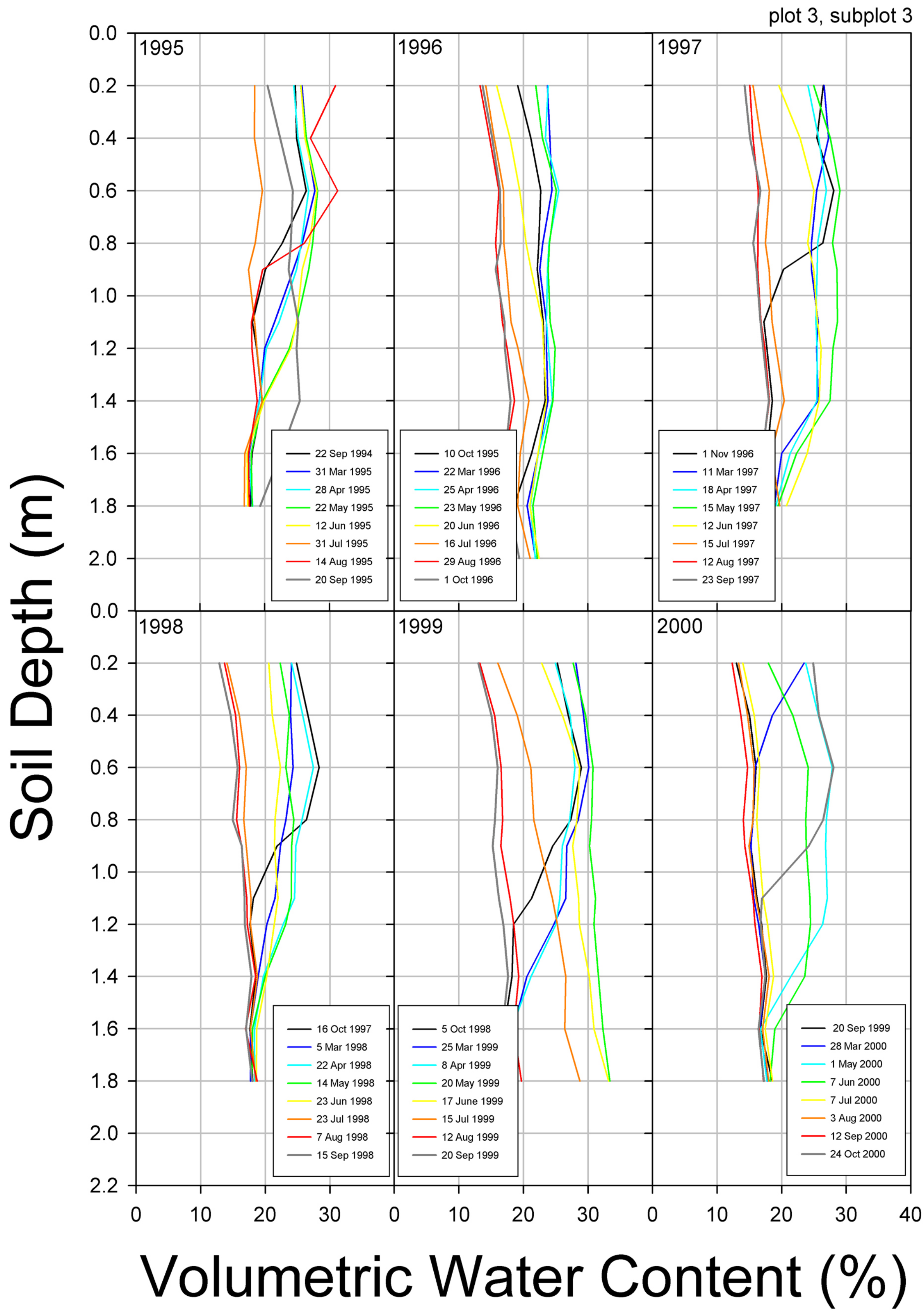

plot 3, subplot 3
1995
1996
1997
1998
1999
2000
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000
Soil Depth (m)
Volumetric Water Content (%)

Figure 30. Soil moisture profiles for a native-vegetation/shallow-biobarrier cap receiving fall/spring for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 2-3 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Fall/spring irrigation treatments were initiated in August, 1995.

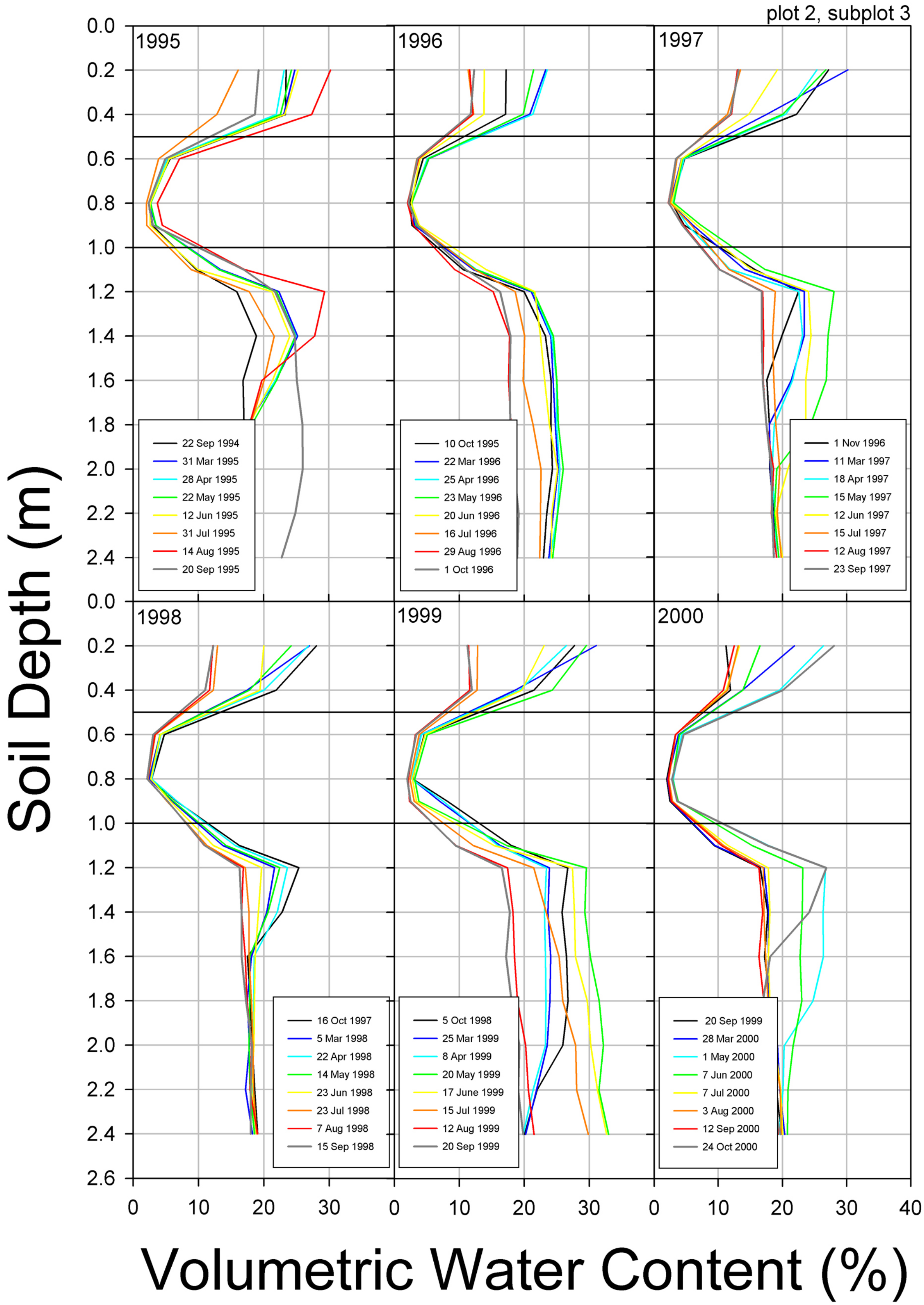
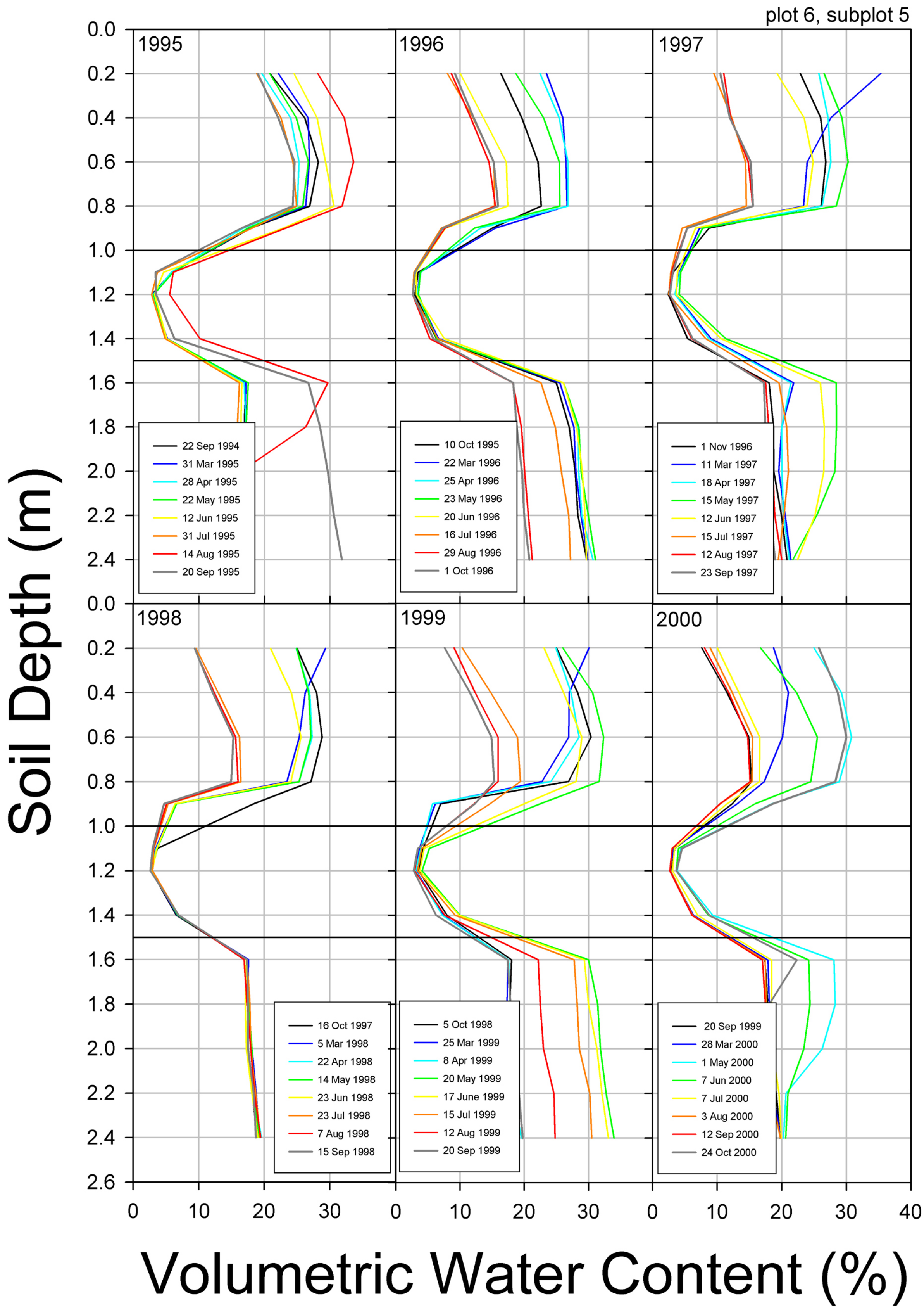

plot 2, subplot 3
1995
1996
1997
1998
1999
2000
Soil Depth (m)
Volumetric Water Content (%)
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000

Figure 31. Soil moisture profiles for a native-vegetation/deep-biobarrier cap receiving fall/spring for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 6-5 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Fall/spring irrigation treatments were initiated in August, 1995.



plot 6, subplot 5
1995
1996
1997
1998
1999
2000
Soil Depth (m)
Volumetric Water Content (%)
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000

Figure 32. Soil moisture profiles for a native-vegetation/RCRA cap receiving fall/spring for years 1995 – 2000. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplot 12-1 of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. See Section 2.3 for cap descriptions. Fall/spring irrigation treatments were initiated in August, 1995.

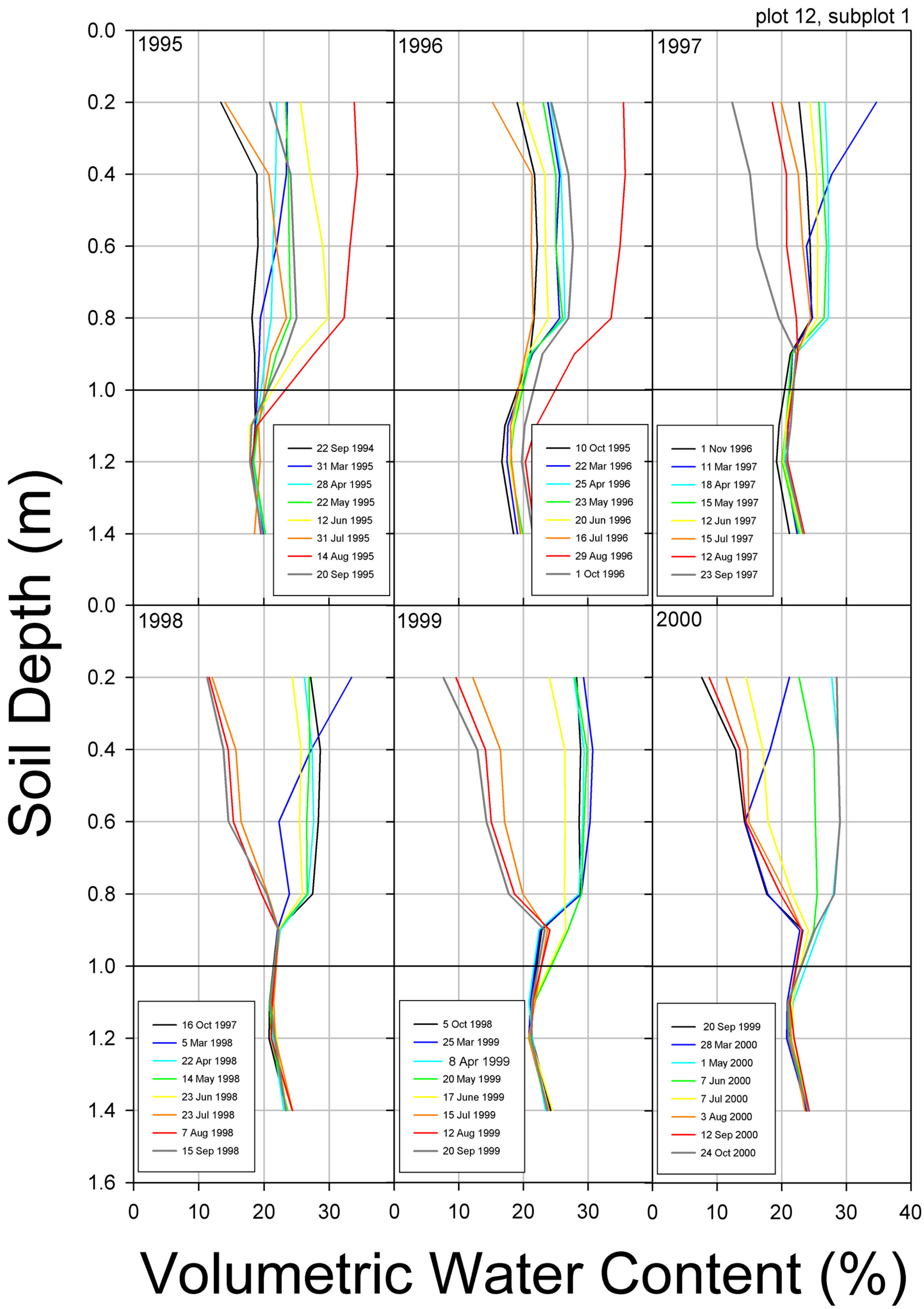

plot 12, subplot 1
Soil Depth (m)
Volumetric Water Content (%)
1995
22 Sep 1994
31 Mar 1995
28 Apr 1995
22 May 1995
12 Jun 1995
31 Jul 1995
14 Aug 1995
20 Sep 1995
1996
10 Oct 1995
22 Mar 1996
25 Apr 1996
23 May 1996
20 Jun 1996
16 Jul 1996
29 Aug 1996
1 Oct 1996
1997
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
1998
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
1999
5 Oct 1998
25 Mar 1999
8 Apr 1999
20 May 1999
17 June 1999
15 Jul 1999
12 Aug 1999
20 Sep 1999
2000
20 Sep 1999
28 Mar 2000
1 May 2000
7 Jun 2000
7 Jul 2000
3 Aug 2000
12 Sep 2000
24 Oct 2000

Figure 33. Soil moisture profiles in 1998 for all soil-only subplots receiving fall/spring irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.

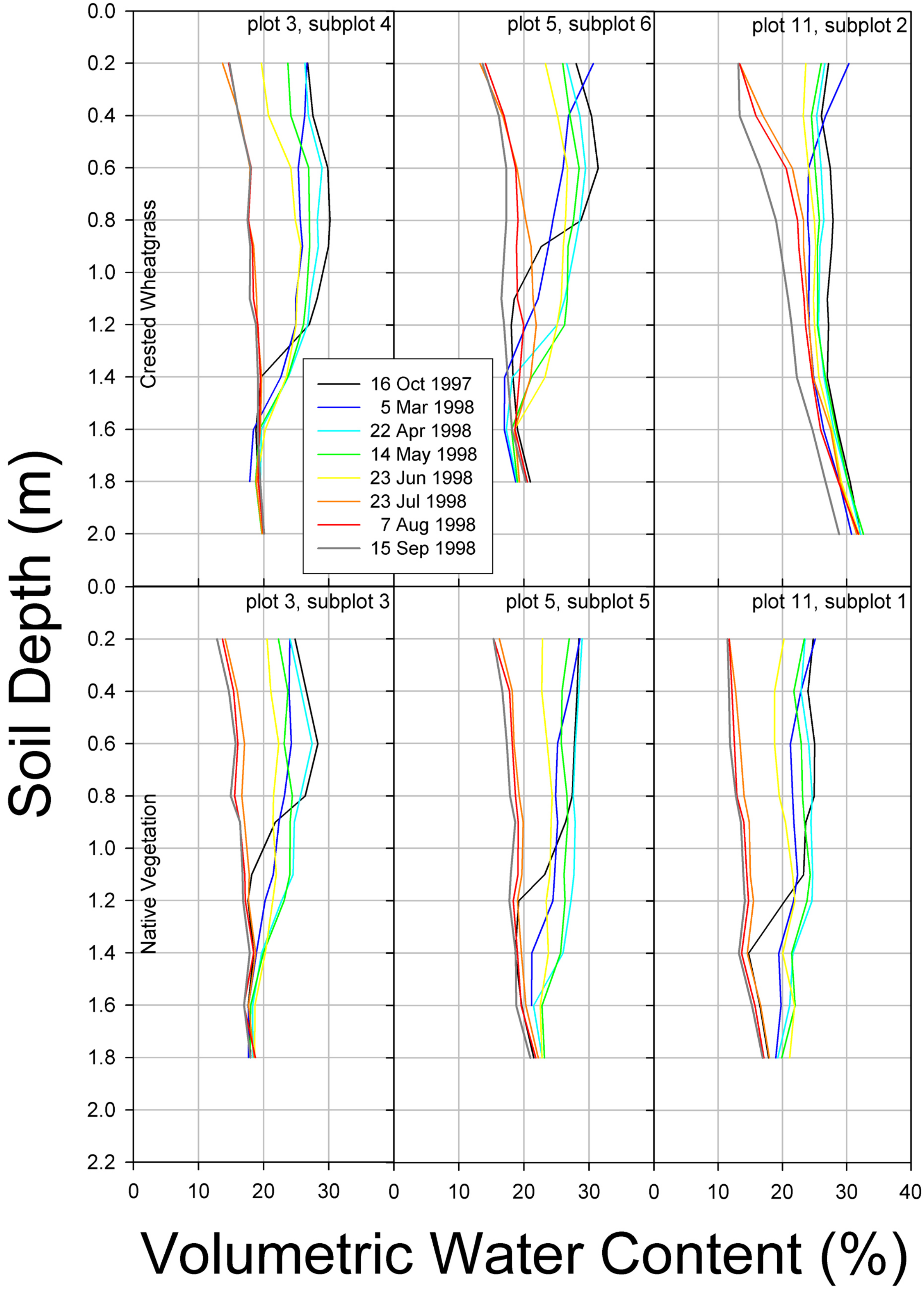

plot 3, subplot 4
plot 5, subplot 6
plot 11, subplot 2
plot 3, subplot 3
plot 5, subplot 5
plot 11, subplot 1
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 34. Soil moisture profiles in 1998 for all shallow-biobarrier subplots receiving fall/spring irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.

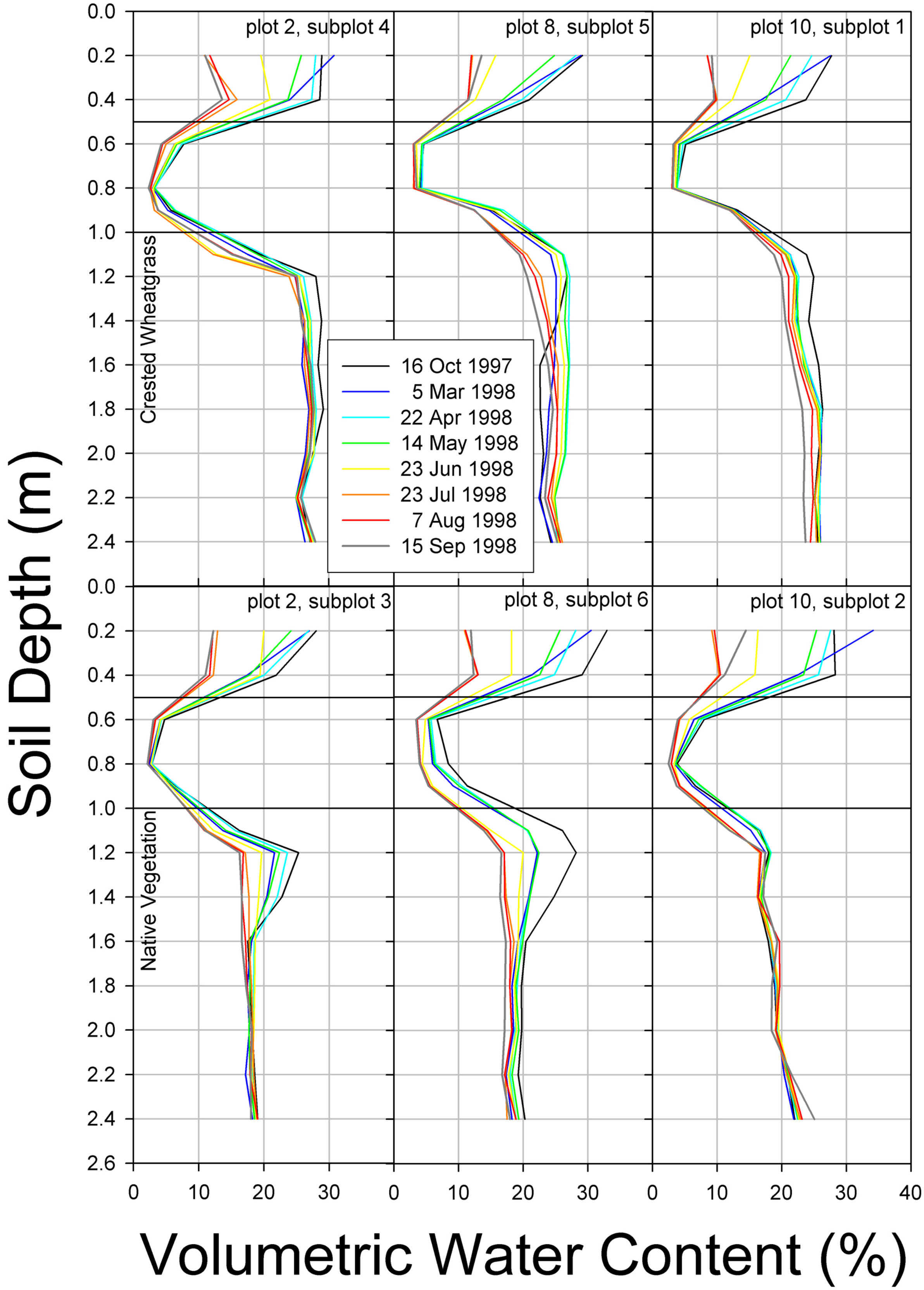

plot 2, subplot 4
plot 8, subplot 5
plot 10, subplot 1
plot 2, subplot 3
plot 8, subplot 6
plot 10, subplot 2
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 35. Soil moisture profiles in 1998 for all deep-biobarrier subplots receiving fall/spring irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.

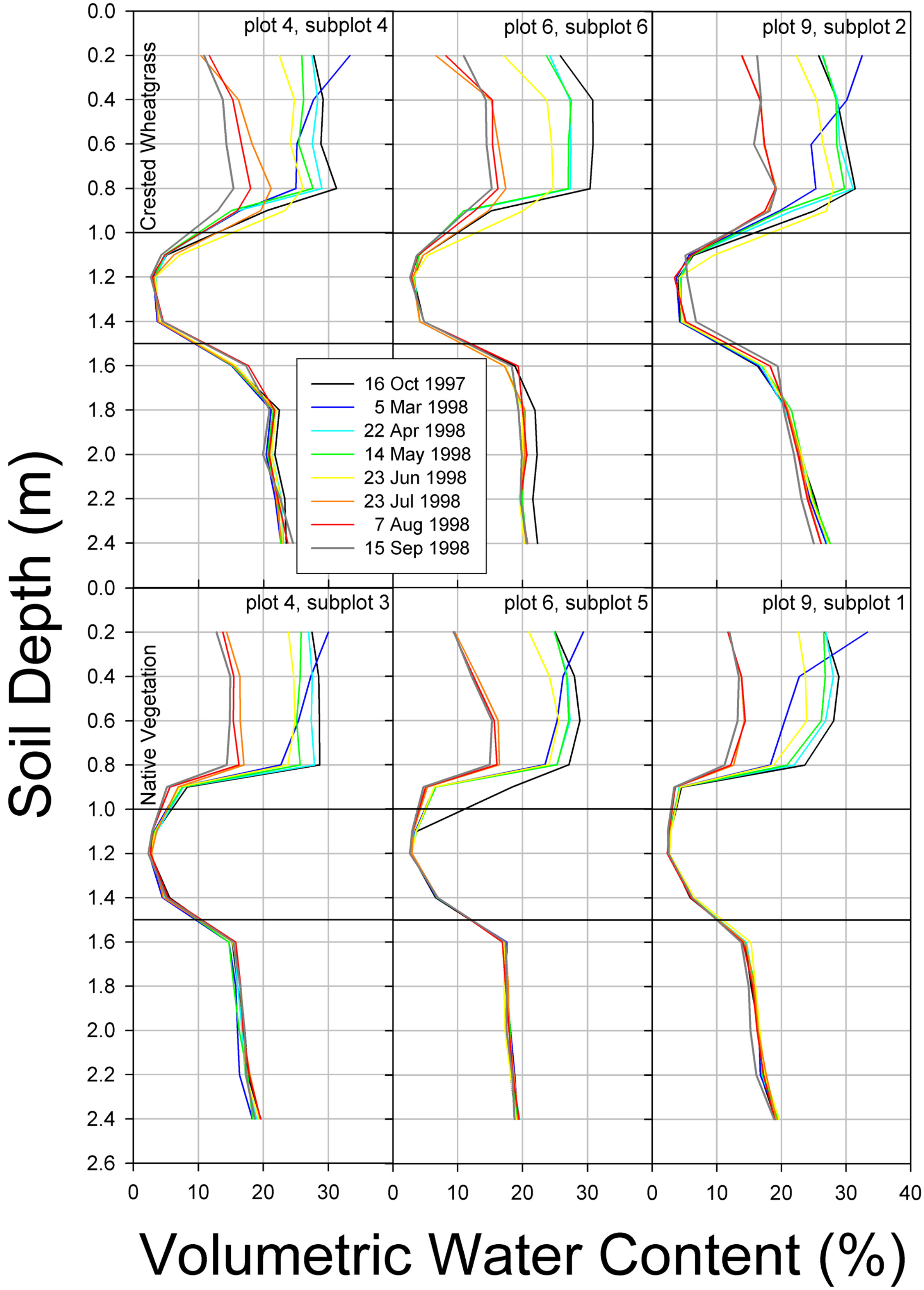
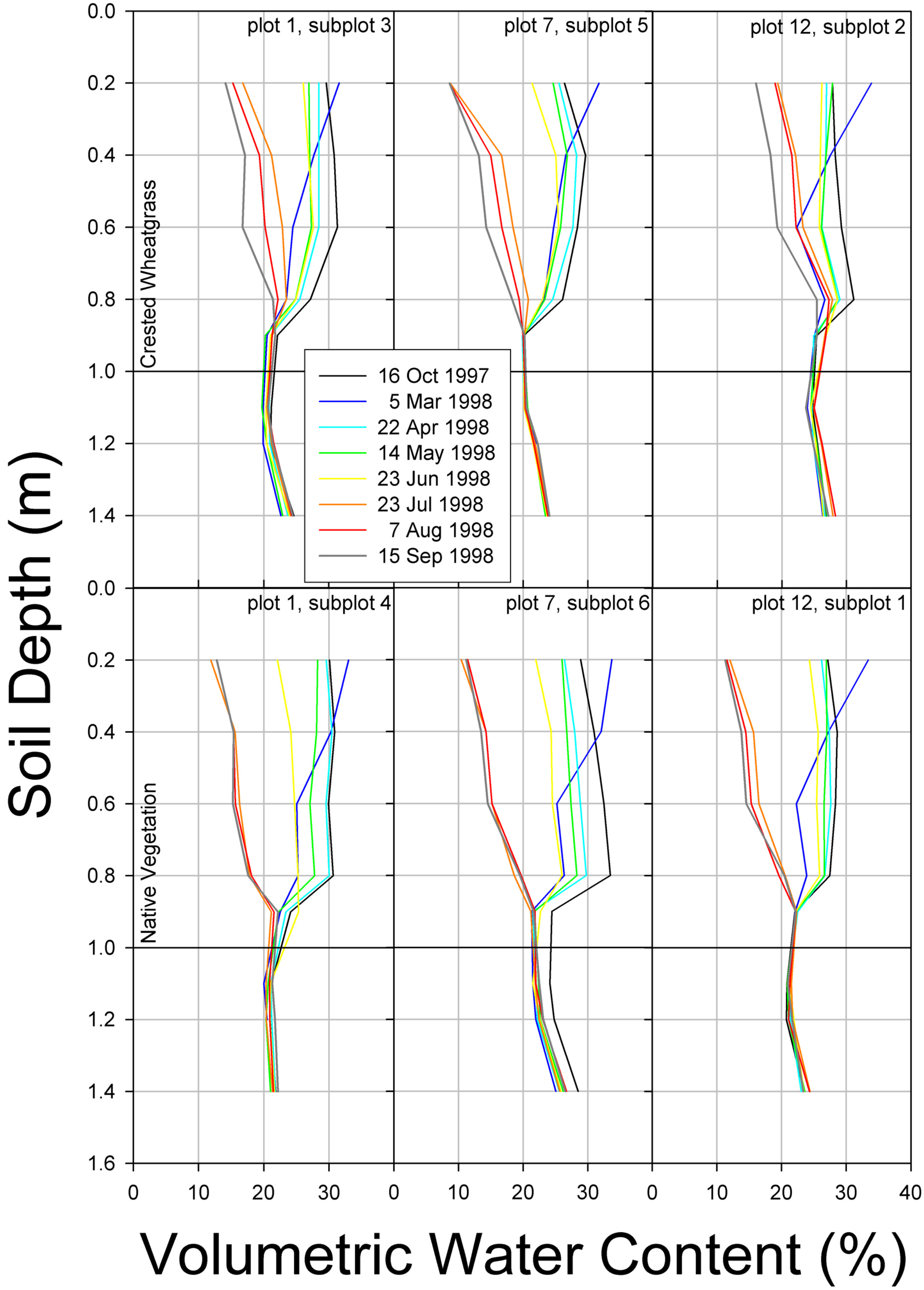

plot 4, subplot 4
plot 6, subplot 6
plot 9, subplot 2
plot 4, subplot 3
plot 6, subplot 5
plot 9, subplot 1
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 36. Soil moisture profiles in 1998 for all RCRA subplots receiving fall/spring irrigation. Crested-wheatgrass replicates are shown in the upper frame; native-vegetation replicates are shown in the lower frame. Each line depicts volumetric water content as a function of soil depth for a particular sampling date.



Soil Depth (m)
Volumetric Water Content (%)
plot 1, subplot 3
plot 7, subplot 5
plot 12, subplot 2
plot 1, subplot 4
plot 7, subplot 6
plot 12, subplot 1
Crested Wheatgrass
Native Vegetation
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
0
10
20
30
40

Figure 37. Soil moisture profiles in 1997 and 1998 for a soil-only, shallow-biobarrier, and deep-biobarrier plot that were accidentally irrigated in August of 1996 due to failure of an irrigation valve. Water content on each of these plots was above field capacity by the end of the 1996 growing season (see line for 1 November 1996 in upper frames). All three plots support native vegetation.

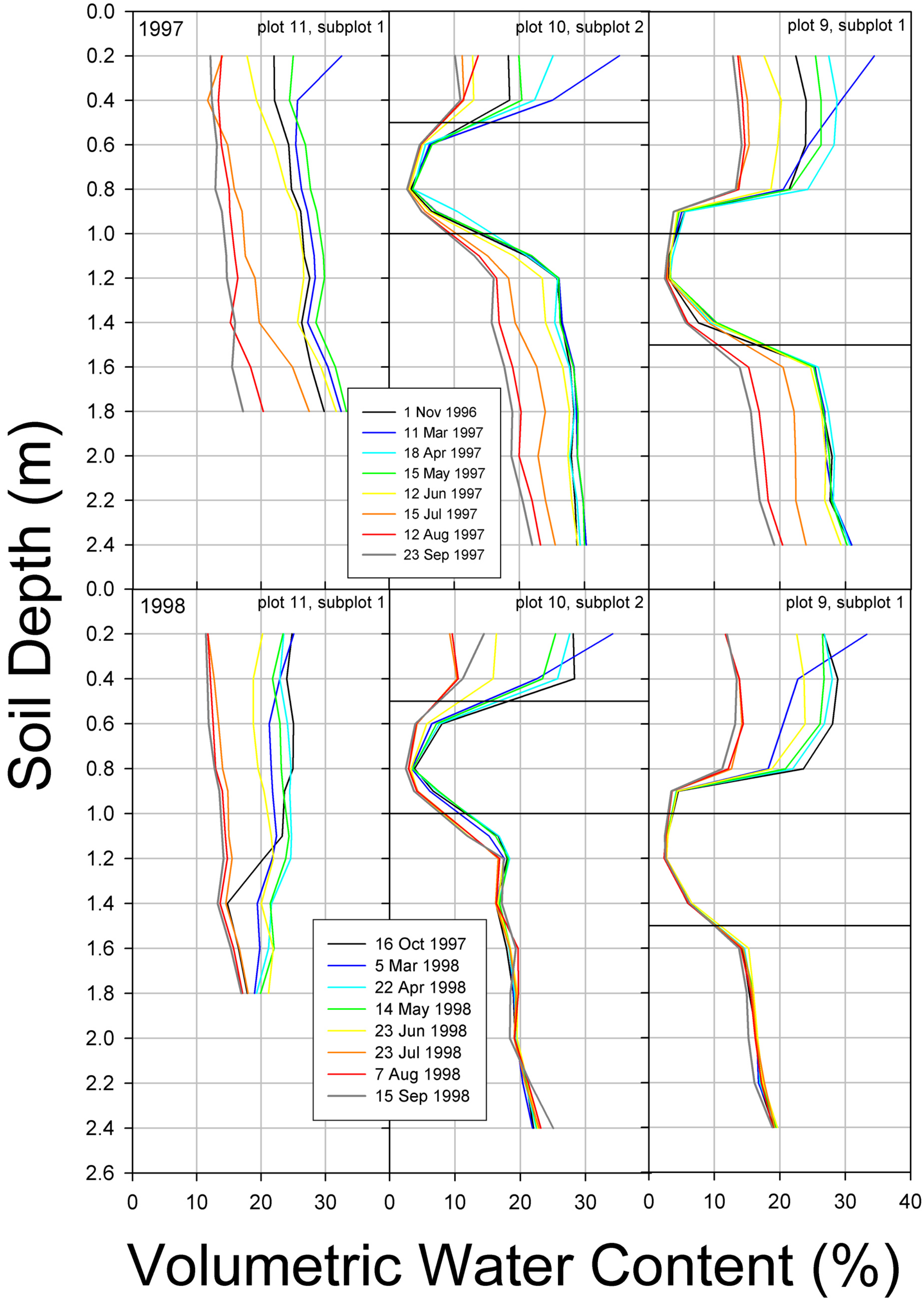

1997
plot 11, subplot 1
plot 10, subplot 2
plot 9, subplot 1
1 Nov 1996
11 Mar 1997
18 Apr 1997
15 May 1997
12 Jun 1997
15 Jul 1997
12 Aug 1997
23 Sep 1997
1998
plot 11, subplot 1
plot 10, subplot 2
plot 9, subplot 1
16 Oct 1997
5 Mar 1998
22 Apr 1998
14 May 1998
23 Jun 1998
23 Jul 1998
7 Aug 1998
15 Sep 1998
Soil Depth (m)
Volumetric Water Content (%)

Figure 38. Average plant cover in 2000 on crested-wheatgrass and native-vegetation subplots of the four ET cap configurations of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Error bars are ± 1 S.E.

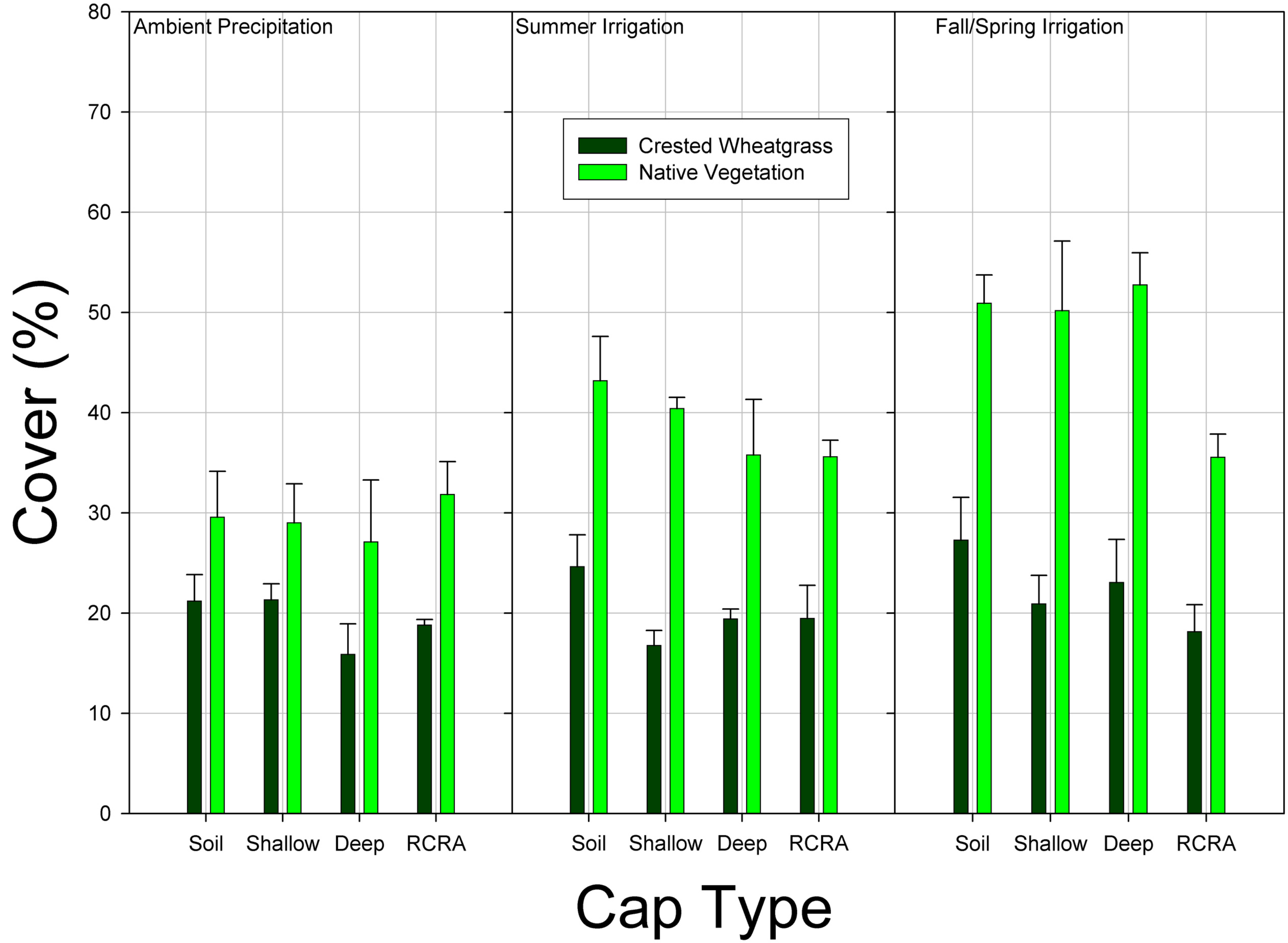
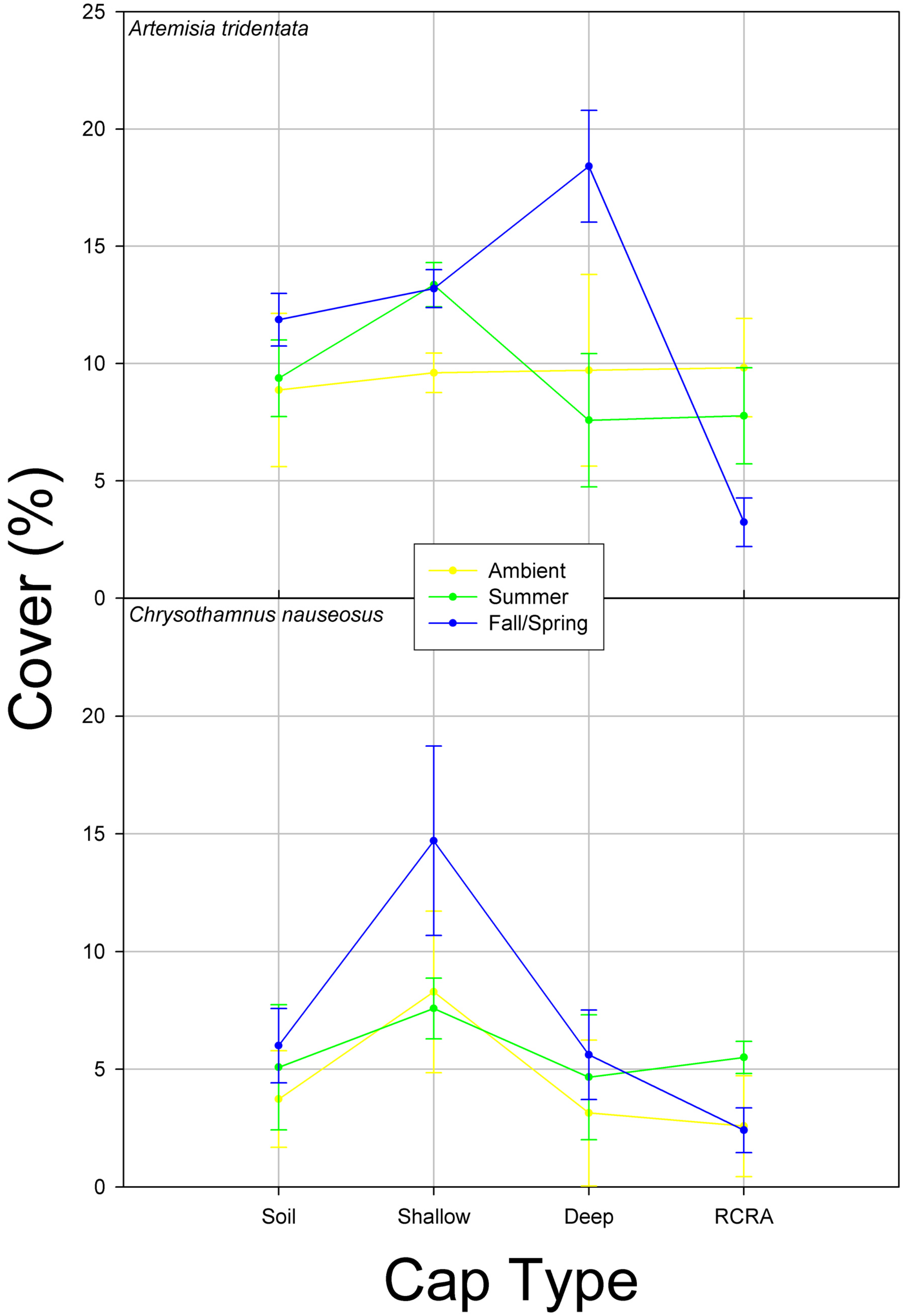

Ambient Precipitation
Summer Irrigation
Fall/Spring Irrigation
Crested Wheatgrass
Native Vegetation
Cover (%)
0
10
20
30
40
50
60
70
80
Soil
Shallow
Deep
RCRA
Cap Type

Figure 39. Average cover of sagebrush (*Artemisia tridentata*) and gray rabbitbrush (*Chrysothamnus nauseosus*) receiving three precipitation/irrigation treatments on the four ET caps of the Protective Cap/Biobarrier Experiment at the Idaho National Engineering and Environmental Laboratory. Ambient refers to ambient precipitation, summer refers to summer irrigation (200 mm applied in 50-mm increments at two-week intervals), and fall/spring refers to 200 mm of irrigation applied in late fall or early spring (See Section 2.8 for irrigation details). Data are from 2000. Error bars are ± 1 S.E.



Artemisia tridentata
Chrysothamnus nauseosus
Ambient
Summer
Fall/Spring
Cover (%)
Cap Type
Soil
Shallow
Deep
RCRA
0
5
10
15
20
25