STOLLER-ESER-101

PCBE Revisited:
Long-Term Performance of Alternative Evapotranspiration Caps for Protecting Shallowly Buried Wastes Under Variable Precipitation

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Long-Term Performance of Alternative Evapotranspiration Caps for Protecting Shallowly Buried Wastes Under Variable Precipitation

Brandy C. Janzen, Matthew J. Germino, Jay E. Anderson[1]
Department of Biological Sciences
Idaho State University
Pocatello, ID 83209

Amy D. Forman
S.M. Stoller Corporation
Idaho Falls, ID 83401

Prepared by:

Prepared for:

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[1] Deceased

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EXECUTIVE SUMMARY

Relationships of plant cover and soil water content were evaluated for the years 2002-2006 of the Protective Cap/Biobarrier Experiment (PCBE). This experiment is designed to test the effectiveness of alternative evapotranspiration (ET) cap designs for protecting shallowly buried wastes at the Idaho National Laboratory (INL). Data collection on the PCBE began in 1994 and findings to 2000 were reported previously by Anderson and Forman (2002, 2003). Comparisons of the 1994-2000 and the 2002-2006 study periods offer a rare opportunity to examine the dynamic performance of ET caps following episodic drought, because the most significant drought in at least the past 54 years began at the end of the first study period and ended during the second study period. Successful performance of ET caps during climatic fluctuations is crucial to long-term protection of shallowly buried wastes. Specifically, resumption of soil water use by plants on ET caps and protection of wastes from soil water is a concern following episodic drought.

Many plant cover and soil water patterns reported for the 1994-2000 study were observed again in the 2002-2006 study. However, there appeared to be a higher incidence of water accumulation in excess of predicted field capacity at the bottom of ET caps in 2002-2006 than in 1994-2000. Such water accumulation is here after referred to as a "potential breakthrough." We did not directly measure water content below the caps. One of the ET caps previously deemed to be most suitable for protection of interred wastes – a cap comprised only of 2 m of topsoil – had among the most frequent and highest levels of water accumulation at the bottom of the cap during 2002-2006. The top performing cap appeared to be one having a layer of cobble at 1 m depth, within 2 m layer of topsoil ("deep-biobarrier") planted with native vegetation. In contrast to the previous report and to our predictions, EPA recommended caps appeared to function well, despite having the least plant cover of all cap types. However, EPA caps generate runoff which must be disposed of properly, and there were several cases of soil moisture below the flexible membrance liner (FML) beneath the cap, indicating cap failure.

As reported previously, a diverse mix of native vegetation provided better water storage on ET caps than monocultures of crested wheatgrass. Crested wheatgrass does not appear adequate for ET cap function except under a narrow set of climatic and cap configuration conditions.

Similar to the 1994-2000 study, subplots receiving ambient precipitation or supplemental summer irrigation generally did not have appreciable water accumulation at the bottom of the caps during the 2002-2006 study. However, subplots receiving fall/spring irrigation frequently had water accumulation at the bottom of caps. Surprisingly, subplots receiving supplemental summer irrigation tended to have the least water accumulation at the bottom of the caps and had the greatest cover values, especially following extended drought years.

We asked whether differences in vegetation cover could explain changes in cap performance between the 1994-2000 and 2002-2006 study periods. Lower values of plant cover did occur in some years of 2002-2006 compared to previous study years. Moreover, there tended to be less plant cover on subplots planted with crested wheatgrass that had frequent breakthroughs. Cover of crested wheatgrass subplots was also more variable in both abundance and species composition, from year-to-year and among different cap types compared to subplots planted with native vegetation. Variability in species composition resulted from encroachment by non-crested wheatgrass species into subplots planted with crested wheatgrass, which was much greater than encroachment of crested wheatgrass into native plantings. Variability in native vegetation and crested wheatgrass was positively correlated with precipitation. However, the significance of plant cover variations to ET cap function is undermined by weak correlations of cover and evapotranspiration in the 2002-2006 data. Direct measurements of ET and more frequent cover measurements are needed to better understand how plant cover affects ET cap performance.

These findings indicate that simple paradigms of soil-plant water relationships may not be adequate to explain the performance of ET caps. In particular, further research is needed to assess i) how plant cover affects ET, to guide planting strategies, ii) how antecedent moisture affects cap ET following wetting, and iii) how species identity and timing of precipitation affect ET.

List of Abbreviations and Acronyms

ANOVA	Analysis of Variance
CFA	Central Facilities Area
CV	Coefficient of Variance
EPA	U.S. Environmental Protection Agency
ET	Evapotranspiration
FML	Flexible Membrane Liner
GRI	Gas Research Institute
INL	Idaho National Laboratory
NOAA	National Oceanic & Atmospheric Administration
PCBE	Protective Cap/Biobarrier Experiment
RCRA	Resource Conservation and Recovery Act
SD	Standard Deviation
SE	Standard Error
VWC	Volumetric Water Content

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1.0 Introduction

Shallow burial of industrial, municipal, and low-level radioactive waste is commonly used as the preferred method of disposal (Anderson and Forman 2003). Water movement into shallowly buried waste materials must be prevented to avoid subsequent leaching of hazardous material into groundwater or re-deposition on the surface as a result of plant uptake (Bowerman and Redente 1998; Daniel and Gross 1995; Suter et al. 1993). The Environmental Protection Agency (EPA) recommends that shallowly buried wastes in arid environments are covered with a compacted clay layer overlain by a synthetic non-permeable liner (flexible membrane liner; FML) and a "cap" of vegetated topsoil (USEPA 1989). The soil-vegetation cap is meant to deplete soil water and prevent percolation of precipitation, and is known as evapotranspiration (ET) cap. The recommended EPA design is both expensive and commonly fails to prevent percolation of precipitation into interred wastes in arid environments (Daniel and Gross 1995; Suter et al. 1993). The Resource Conservation and Recovery Act (RCRA) regulations allow for alternative cap designs, under the condition that specific performance standards can be met (Forman and Anderson 2005).

The Idaho National Laboratory (INL) began research on the effectiveness of ET caps for protection of buried wastes in 1983 (Anderson et al. 1987, 1991, 1993). A primary objective of these studies was (and currently is) to evaluate the possibility that RCRA performance standards can be met by alternative cap configurations in the long-term, and to identify differences between the effectiveness of native communities and crested wheatgrass (*Agropyron cristatum* and *A. desertorum*) monocultures.

Long-term cap performance requires persistence of vegetative cover that can reliably deplete soil water, thereby avoiding excessive percolation below the cap in addition to allowing for storage of future precipitation in soil. Annual precipitation is not only relatively scarce in arid and semiarid environments, but also tends to be more variable within and among years compared to in more mesic environments. As a result of this variability, successful ET caps in dry environments must be both dynamic and responsive in order to cope with episodic drought and years of abnormally high precipitation. In addition to yearly fluctuations in precipitation, ET caps must also be designed to perform as long-term climatic conditions in these regions evolve.

The focus of the current report is to assess performance of experimental ET caps constructed at INL in 1993 for the years 2002 to 2006. Vegetation cover and soil water patterns in these caps from 1994-2000 were described in Anderson and Forman (2003), and data collection by the Environmental Surveillance, Education, and Research Program (ESER) has continued through 2006. The years following Anderson and Forman's (2003) report are particularly valuable for assessing long-term performance of ET caps at INL because these years encompass some of the greatest variation in yearly precipitation since 1950 (Figure 1). 2001 to 2003 were drier than any of the preceding 50 years. Prolonged drought, followed by above average precipitation during the 2002-2006 study allowed for key tests of cap performance. Specifically, the ability of ET caps to reliably deplete soil water during and following drought cycles, one of the greatest challenges for ET caps. Following drought, soil water use and water storage capabilities of ET caps may be compromised by reductions in vegetation cover and water use during drought years. The current report is poised to assess ET cap performance under episodic drought, as the last years described in the Anderson and Forman (2003) report were the beginning of an unusual drought that appears to have ended in about 2004.

1.1 Initial ET Cap Research at INL

Ten initial ET caps were created at INL in 1983 with the intention of examining the ability of four perennial plants; sagebrush (*Atremisia tridentata* ssp. *tridentata* and *wyomingensis*), crested wheatgrass, Great Basin wildrye (*Leymus cinereus*), and stream-bank wheatgrass (*Elymus lanceolatus*), to deplete soil moisture within these caps (Anderson et al. 1987, 1991, 1993; as reported in Anderson and Forman 2003). These studies reported that all four planted perennial specieswere able to sufficiently deplete soil

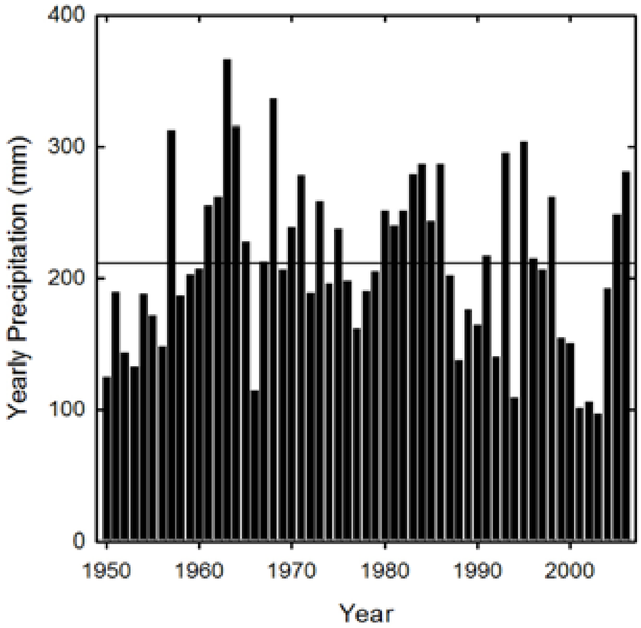


Figure 1: Yearly precipitation (mm), from 1950 to 2006, and 56 year average (210 mm). Data acquired from the Central Facilities Area (CFA) weather station from unpublished NOAA data.

moisture to a depth of 2.2 m, even under relatively wet conditions. Since these first INL studies, ET cap research was directed at performance of caps having i) grass monocultures or diverse, native species mixes, ii) varying depths of soil, with and without flexible membrane liners (FMLs) or biological intrusion barriers (biobarriers), and iii) varying amounts of annual precipitation. Biobarriers are layers of cobble in soil that are used to prevent impacts of burrowing animals on movement of wastes to the surface, on soil water dynamics, and to provide a capillary break to minimize percolation into deeper soils. In 1993, the Protective Cap/Biobarrier Experiment (PCBE) was initiated in order to address these concerns. The PCBE strived to confidently recommend a cap configuration that could successfully limit percolation of precipitation into shallowly buried waste in semiarid and variable climates and prevent biointrusions while maintaining a healthy, sustainable plant community.

The objectives of Anderson and Forman's report (2003) of the PCBE during 1994-2000 were: 1) to compare the hydrologic performance of four ET cap designs, 2) examine the effects of biobarriers on water movement and utilization of soil water throughout the soil profile, 3) compare performance of different cap types under current and forecasted precipitation regimes, and 4) compare performances of diverse native communities to that of monocultures of crested wheatgrass.

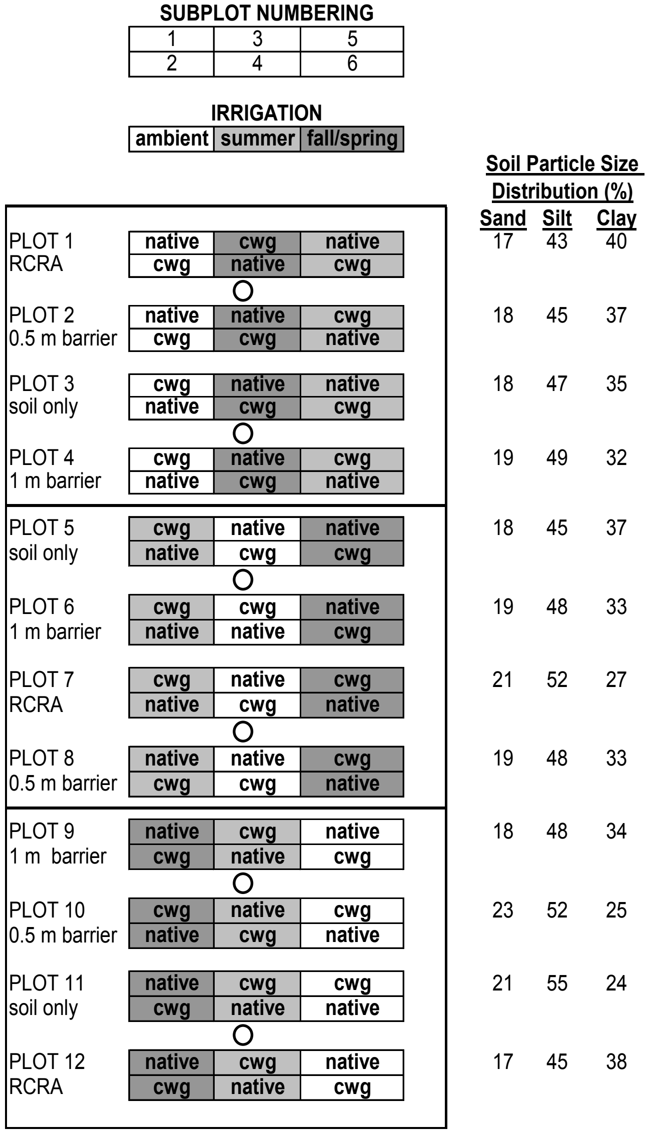
1.2 The Protective Cap Biobarrier Experiment

1.2.1 Experimental Design of the PCBE

The PCBE design consists of twelve main plots that are replicates of four cap configurations (Figure 2). Each main plot is divided into six, eight by eight meter subplots representing both native vegetation or crested wheatgrass plantings, and either ambient precipitation, supplemental summer, or supplemental fall/spring irrigation.

The four cap configurations (Figure 3) include i) a soil-only cap type consisting of 2 m of vegetated topsoil, ii), a shallow biobarrier cap having a total of 2 m of topsoil and a 0.5 m biobarrier at 0.5 m depth iii) a deep biobarrier cap with the same attributes as the shallow biobarrier cap expect the biobarrier is placed at 1 m depth, and iv) the EPA/RCRA regulation design with 1 m (instead of 0.6 m) of topsoil and a 0.6 m clay layer and a FML on a 3 percent slope to allow runoff. The biobarriers are constructed of 0.3 m of cobble (0.1 – 0.2 m in diameter) in between 0.1 m thick layers of gravel (5 – 15 mm in diameter). All cap configurations are underlain by layer of gravel.

Three precipitation regimes are used in the PCBE, to mimic current and predicted precipitation patterns. An ambient precipitation regime has no supplemental irrigation. The summer precipitation regime includes supplemental irrigation of 50 mm applied biweekly beginning in mid-June until a total of 200 mm of water has been applied. The fall/spring precipitation regime has supplemental irrigation of 200 mm applied in October or in April within a short-time period (one to two weeks). The quantity of water added in summer and fall/spring irrigation regimes is intended to mimic extreme weather events.



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 2: Layout of the PCBE. The 12 main plots are replicates of the four cap configurations. Each main plot is divided into six subplots representing the two vegetation types and three irrigation treatments. The position of six caissons is shown as bold circles between plots. Soil texture data corresponding to each main plot is shown to the right of the layout. Cwg = crested wheatgrass; native = native vegetation (Anderson and Forman 2002).

Two vegetation communities were planted on PCBE caps, a diverse native community or a monoculture of crested wheatgrass. The native vegetation community included five shrubs, five perennial grasses, and two forbs (Table 1). Crested wheatgrass is no longer planted on new ET caps at INL, but there are existing caps with crested wheatgrass, and the function of these caps is of concern.

The PCBE cap design was constructed to allow for strip, split-plot analysis of variance (ANOVA, Anderson and Forman 2002). However, the experimental design had low power and was therefore treated as a completely random sample design for all ANOVA tests. Though this approach violates key assumptions of the statistical analysis, it allows for the identification of potential differences between treatments (Anderson and Forman 2002). Moreover, irrigation and species treatments were randomly applied to subplots, minimizing deviation from a true, completely randomized design. Cover values for subplots are measured using point intercept frames starting at the end of June until completion, approximately one month later. Soil water content is measured biweekly during the growing season, using the neutron moderating technique, in access tubes in the center of each plot (Anderson and Forman 2002).

1.2.2 Findings from Anderson & Forman (2003)

Precipitation during the initial, 1994-2000 years of the PCBE ranged from 318 mm to 129 mm, in the 1994/1995 and 1999/2000 seasons, respectively. Native vegetation was the primary focus of plot cover assessments for the 1994-2000 study, though cover was reported to be greater in subplots planted with native vegetation compared to crested wheatgrass by the end of the study period. Supplemental fall/spring irrigation generally increased cover, especially on plots with soil-only and deep biobarrier caps and following above-average precipitation (1997).

During the 1994-2000 study, there were no significant differences in growing season ET (calculated as the sum of received precipitation and change in the amount of water stored in the soil) between cap types or vegetation types receiving either ambient or summer precipitation. Soil water depletion was satisfactory in the soil-only and both biobarrier cap types, especially under ambient or supplemental summer precipitation. Although potential cap failure was uncommon (though without water content measures underneath caps, it is impossible to truly know if failure occurred), in terms of water accumulation at the bottom of caps, soil in the RCRA cap types generally approached field capacity early in the growing season. These RCRA caps therefore had a limited water storage capacity before drainage from the FML would occur. Subplots of all cap types receiving fall/spring precipitation typically had greater end-of-season volumetric water content (VWC), indicating a reduced capacity to store soil moisture over winter and early in the spring. In general, subplots planted with crested wheatgrass had greater mean end-of-season soil moisture content than did subplots planted with native vegetation.

1.2.3 Objectives of Current Report

The primary goal of this report is to synthesize the 2002-2006 data of the performance of the four cap types and two vegetation communities under ambient precipitation and supplemental irrigation, in comparison to the 1994-2000 study.

Objective 1 – Compare plant cover and soil water changes of four cap types, two species mixes, and three precipitation levels during 2002-2006 with data reported for 1994-2000.

Objective 2 – Assess the stability of total vegetation community cover (i.e. plant abundance) on subplots, both among and within subplots (i.e. in space and time). Determine the extent to which variability in plant cover reflects annual variability in precipitation.

Objective 3 – Assess the stability of species compositions of subplots, by comparing the susceptibility of subplots planted with either native vegetation or crested wheatgrass to invasion by species not originally planted.

Objective 4 – Compare plant cover to

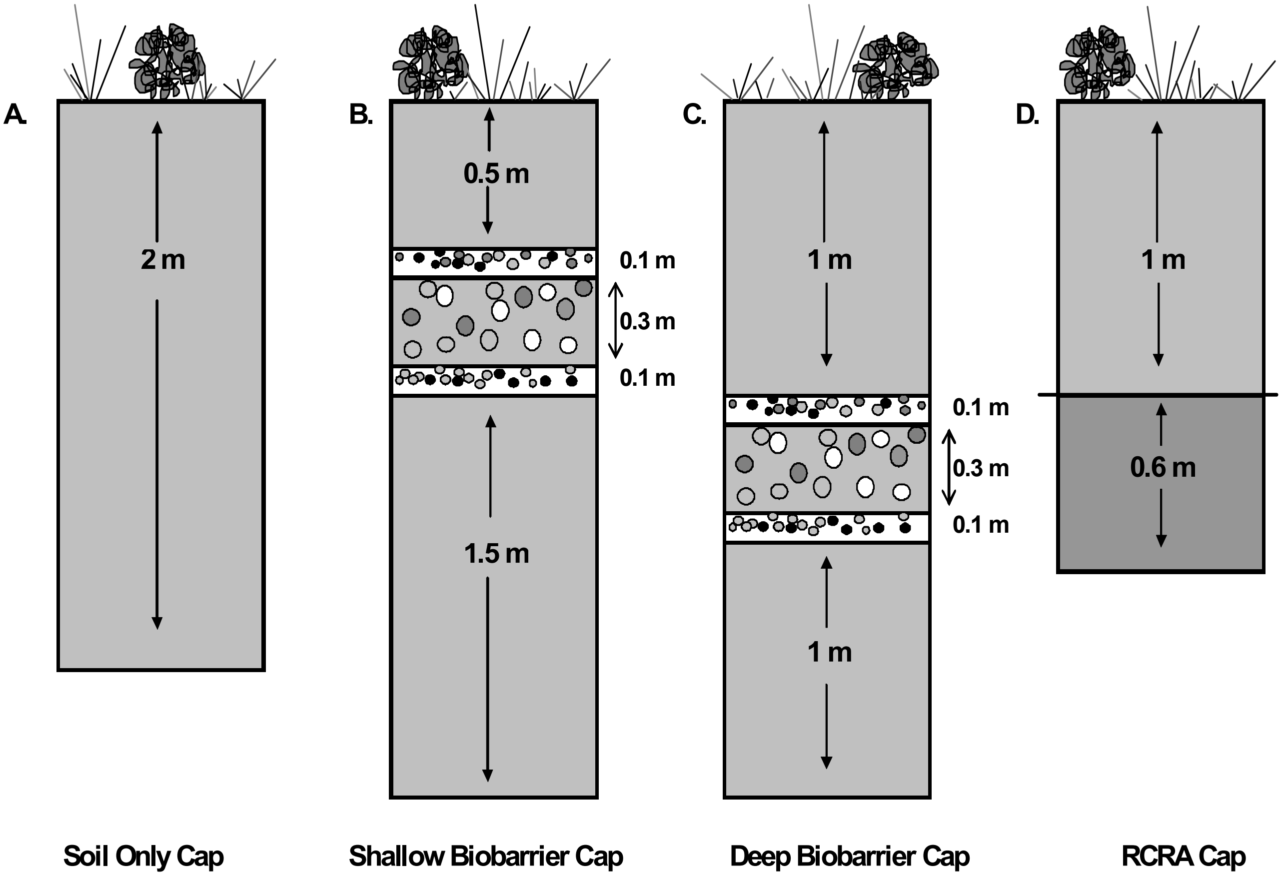


Figure 3: Schematic diagram of vertical sections of the four cap configurations in the PCBE at the INL. Biological intrusion barriers (biobarriers) consist of a 0.3 m depth of cobble sandwiched between 0.1 m depths of gravel (Anderson and Forman 2003).

Table 1: Growth form, common name, and scientific name of species planted onto the native vegetation subplots of the PCBE at the INL (Anderson and Forman 2003).

Growth Form	Common Name	Scientific Name
Shrubs:	Basin big sagebrush	*Artemisia tridentata* ssp. *tridentata*
	Wyoming big sagebrush	*Artemisia tridentata* ssp. *wyomingensis*
	Gray rabbitbrush	*Ericameria 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*

estimates of evapotranspiration, to determine the importance of plant abundance to ET cap function.

We emphasize that the usefulness of the objectives listed above transcends the PCBE study itself. The PCBE offers an excellent opportunity to glean insight on plant-environment relationships that are important for vegetation management in or around INL. For example, the value of plant community diversity and species richness to community productivity, stability, and resistance to invasion are important concerns for land management. Evidence for these relationships in scientific literature is currently equivocal (McNaughton 1997; Tilman et al 1997a, 1997b, Loreau 1998; McCann 2000; Naeem 2000; Purvis and Hector 2000; Wardle et al. 2000, Anderson and Inouye 2001), and so having site-specific assessments of these relationships could be an advantage for successful land management in and around INL.

Stability of vegetation on shallowly buried waste caps could be viewed as a positive attribute provided there is adequate plant cover. On the other hand, year-to-year stability of ET caps that have insufficient cover would probably not be desirable. Similarly, stability of the species composition of a diverse planting of native vegetation is potentially desirable for ET caps at INL, but stability of crested wheatgrass stands perceived to be an invasive problem may not be desirable (Marlette and Anderson 1986). In the current report, we emphasize stability as an important measure of predictability of ET cap structure and function. The climatic conditions experienced by ET caps over long time scales is uncertain, and ideal ET cap designs will reliably persist under whatever future conditions occur.

2.0 RESULTS: 2002-2006 PCBE STUDY

2.1 Precipitation from 2002-2006

The 2002-2006 study included years of above average, near average, and below average precipitation years based upon a 56 year average (Figure 1). The general trend in water-year precipitation during the study period was from unusually dry in 2001-2002 to above average precipitation by 2005 and 2006 (Figure 4). The first years of the study period were some of the driest on record (Western Water Resource Center; NOAA).

The lowest water-year (October-September) precipitation during 2002-2006 (Figure 4) was in 2001/2002 (124 mm) and 2002/2003 (128 mm). The maximum water-year precipitation was in 2005/2006 (250 mm). Most of the variability in precipitation in water years from 2001-2006 was attributable to key pulses in precipitation occurring during winter months or early in the spring.

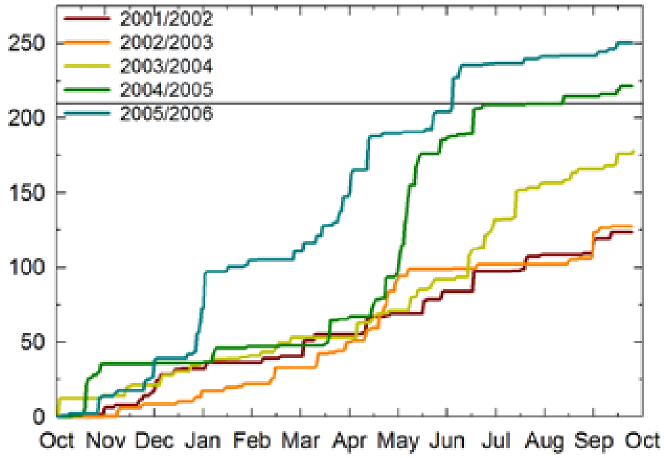


Figure 4: Cumulative water-year (October-September) precipitation for 2002-2006. Data are from the Gas Research Institute (GRI) weather station at Idaho National Laboratory, unpublished NOAA data.

2.2 Vegetation Cover

Vegetation cover from 2002-2006 varied significantly among years, cap types, irrigation regimes, and vegetation types (Table 2). Moreover, vegetation and cap types did not have similar year-to-year variation [Figure 5, comparable to Figure 8 in Anderson and Forman (2003)]. Average cover of all subplots was lowest in 2003 and greatest in 2005 compared to the other years from 2002-2006 (19 percent and 38 percent mean cover of all plots, respectively; $p<0.0001$). Plant cover was lower on RCRA caps compared to other cap types (26 percent mean cover over all years; $p=0.0251$). Maximum mean cover values among caps and years for all precipitation regimes occurred in 2005 on deep-biobarrier caps (65 percent cover; Figure 5). Cover was less on subplots receiving ambient precipitation compared to subplots receiving supplemental irrigation (20 percent mean cover over all years under ambient precipitation; $p<0.0001$). Supplemental irrigation increased cover more when applied in summer (35 percent cover; $p=0.0632$) than when applied in fall/spring (31.1 percent cover).

Cover was lower for subplots planted with crested wheatgrass compared to native vegetation (20 percent mean cover for crested wheatgrass; Figure 5; $p<0.0001$). The greatest mean cover among vegetation types and years was for native vegetation in 2005 and the least cover was in crested wheatgrass subplots in 2003 (49 and 11 percent cover, respectively).

Rank order relationships of cover among plots revealed that of the 30 subplots in the bottom quartile of annual cover values, 90 percent were subplots planted with crested wheatgrass (data not shown). Over all subplots, the lowest cover was in 2004 in the RCRA cap planted with crested wheatgrass and receiving ambient precipitation (5 percent cover). The greatest cover was for a subplot in 2006 in a RCRA cap type planted with native vegetation and receiving supplemental summer irrigation (83 percent cover).

Table 2: Results of 4-way ANOVA comparison of plant cover responses to year of measurement (Year), cap type (Cap), precipitation or irrigation regime (Irr), and planting cover type (Veg). (p<0.05=*, p<0.01=, p<0.001=***).**

Source	DF	Sum of Squares	F Ratio
Year	4	71.1	102.3***
Cap	3	6.8	13.0***
Year*Cap	12	10.5	5.0***
Irr	2	10.8	31.1***
Year*Irr	8	2.5	1.8
Cap*Irr	6	1.6	1.5
Year*Cap*Irr	24	1.1	0.3
Veg	1	11.3	64.8***
Year*Veg	4	5.9	8.5***
Cap*Veg	3	0.1	0.2
Year*Cap*Veg	12	1.4	0.7
Irr*Veg	2	0.2	0.4
Year*Irr*Veg	8	0.5	0.3
Cap*Irr*Veg	6	0.4	0.4
Year*Cap*Irr*Veg	24	0.5	0.1

Stability of species composition, defined here as the abundance of either non-crested wheatgrass species within crested wheatgrass subplots, or crested wheatgrass abundance within native vegetation subplots, was highly variable, particularly within subplots planted with crested wheatgrass. Encroachment of non-crested wheatgrass species into crested wheatgrass subplots was significantly greater than encroachment by crested wheatgrass into subplots planted with native vegetation ($p<0.05$; Figure 6). Although the abundance of crested wheatgrass cover in subplots planted with native species varied significantly among years ($p<0.0001$), it was not statistically related to any other factors. Within the crested wheatgrass subplots, encroachment by non-crested wheatgrass species varied among years ($p<0.0001$) and precipitation regime ($p<0.0001$). Among years, encroachment into crested wheatgrass subplots was significantly greater in the relatively wet years of 2005 and 2006 ($p<0.0001$). Subplots receiving no supplemental irrigation had significantly fewer incidences of encroachment by non-crested wheatgrass species ($p<0.0001$).

2.2.1 Stability of Cover

Stability of vegetation cover was estimated from the coefficient of variance (CV= 100* SD/mean) of cover as it varied among subplots within a year (Figure 7) or within subplots (Figure 8). CV of cover varied among cap types ($p<0.01$; greatest for RCRA caps), and precipitation regime ($p<0.01$; greatest for summer irrigation), and was greater for crested wheatgrass than for native vegetation ($p=0.0001$).

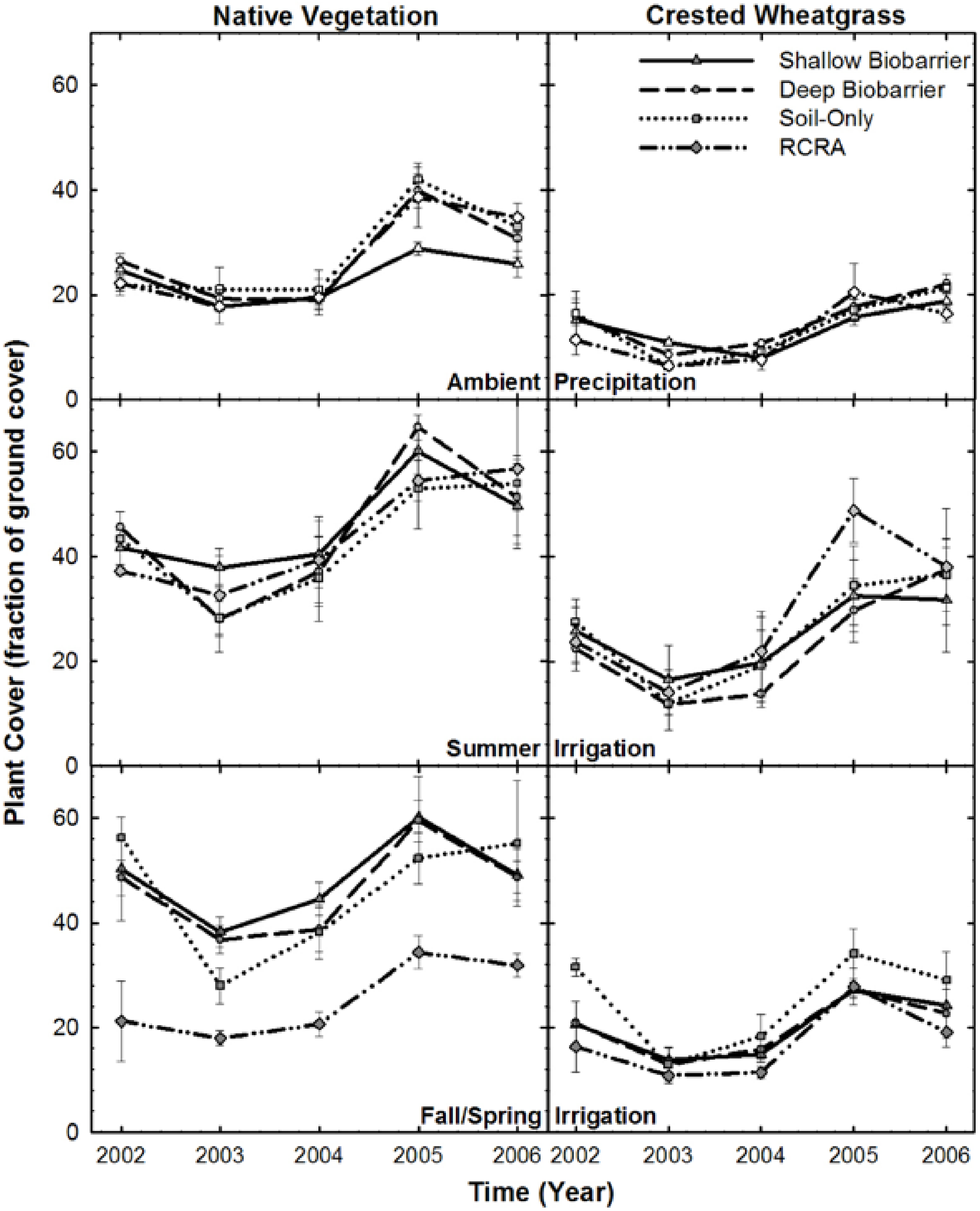


Figure 5: Total plant cover on native vegetation (left panels) and crested wheatgrass subplots (right panels). Errors are ± 1 SE. The same data are plotted differently in Figure 5. See Table 2 for statistics.

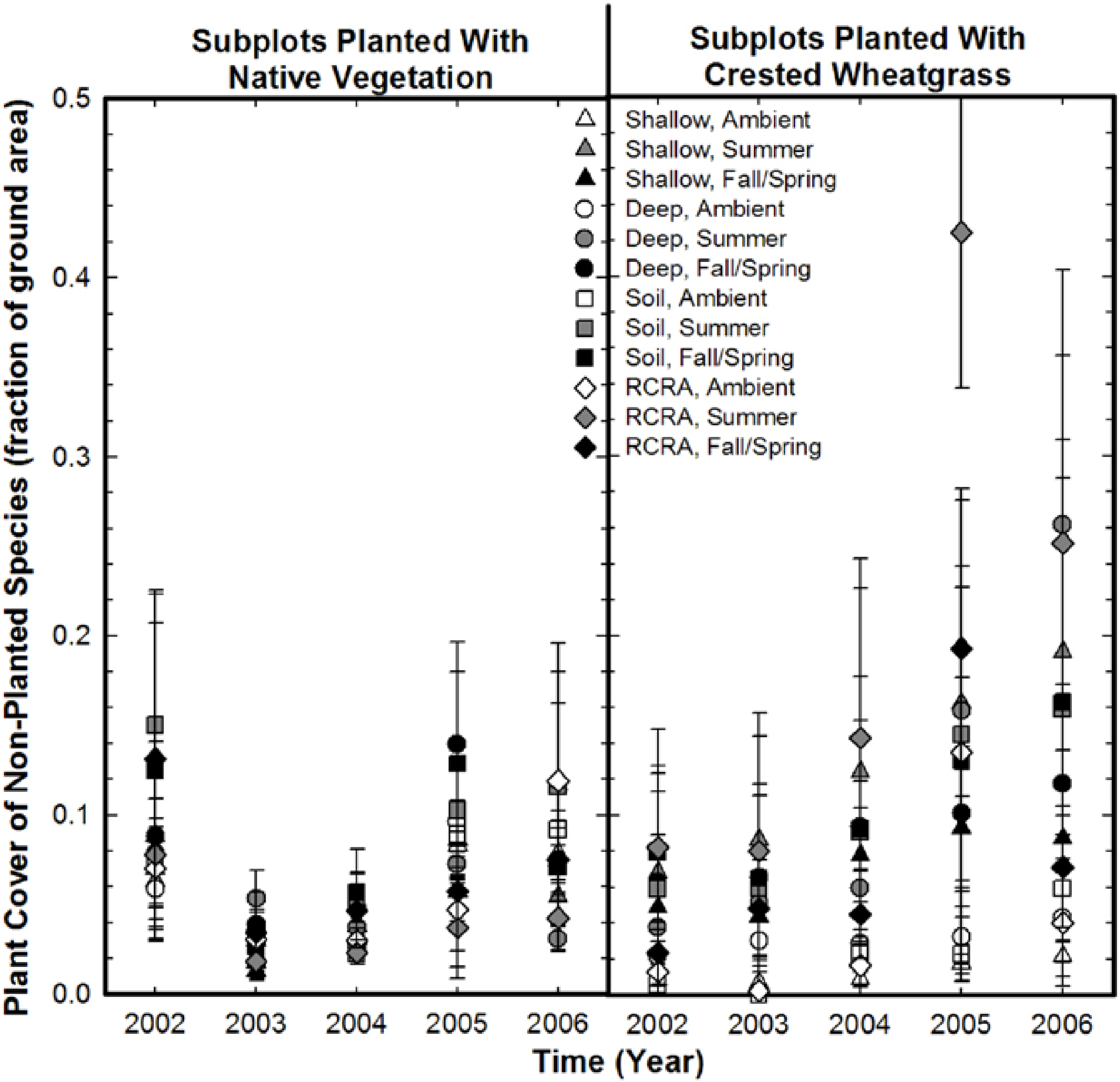


Figure 6: Plant cover of non-planted species as a fraction of total ground cover for Shallow (shallow-biobarrier), Deep (deep-biobarrier), Soil (soil-only), and RCRA cap types under ambient, summer, and fall/spring precipitation regimes. Calculated as the fraction of vegetative cover of crested wheatgrass in native subplots and the fraction of vegetative cover of native vegetation in crested wheatgrass subplots.

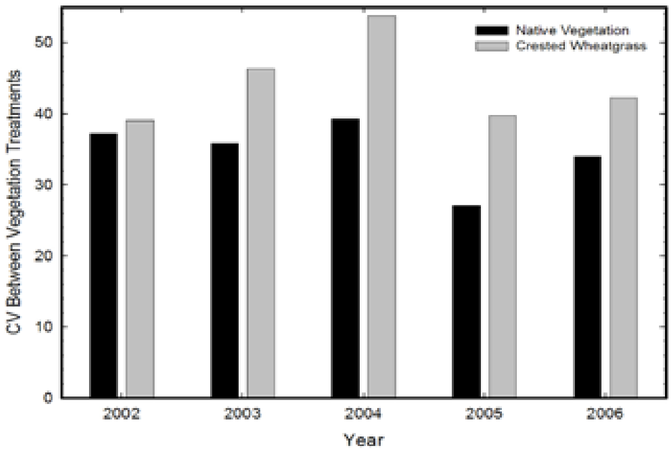


Figure 7: Coefficient of variance (CV) of vegetation cover among plots in each study year, for subplots planted with crested wheatgrass and native vegetation.

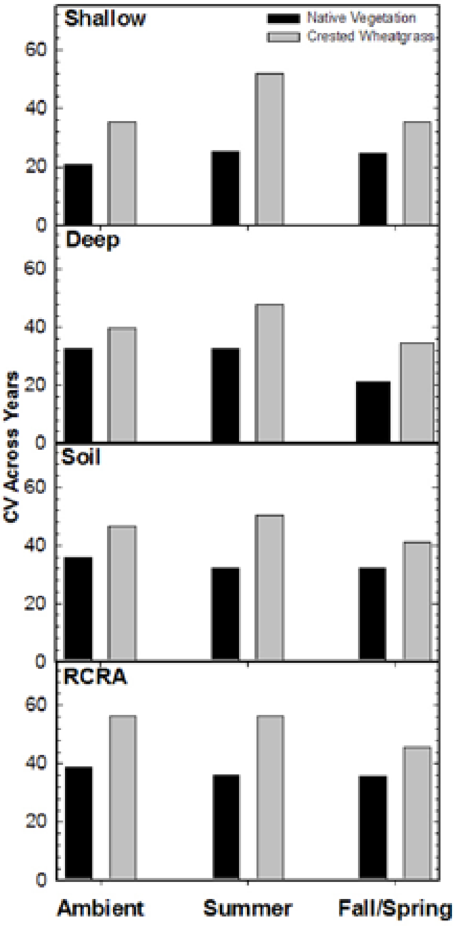


Figure 8: Coefficient of variance (CV) of vegetation cover within each treatments, calculated from the Standard Deviation (SD) and means of the five annual cover values.

2.3 Soil Water Patterns

Volumetric water content (VWC) of soils varied significantly (Table 3) among years, within cap type, irrigation regime (Figure 9), and vegetation type (Figure 10).

Mean VWC was calculated as the VWC at the bottom deepest depth of measurement (VWC_{bottom}). This value in PCBE caps may differ somewhat from actual cap values due to the underlying gravel layer that may act as a capillary break, increasing the field capacity of the soil at this depth. However, comparisons can be made between cap types, precipitation regimes, and vegetation types as a result of all cap types overlying similar gravel layers.

Mean VWC at the deepest depth of measurement was greatest in plots receiving fall/spring precipitation (23.2 percent VWC_{bottom}), and least under ambient precipitation (19.9 percent VWC_{bottom}), though this latter value was not significantly different from subplots receiving supplemental summer irrigation (Table 3). Over all cap types and precipitation regimes, VWC was greater in subplots planted with crested wheatgrass than with native vegetation (21.8 percent and 20.2 percent VWC_{bottom}, respectively). Subplots planted with native vegetation and receiving ambient precipitation had the lowest VWC (18.8 percent VWC_{bottom}), and those planted with crested wheatgrass and receiving fall/spring precipitation had the greatest (23.9 percent VWC_{bottom}), compared to all other combinations of vegetation type and precipitation regime.

Mean VWC was lowest in plots having deep-biobarrier caps (20.3 percent VWC_{bottom}), especially when planted with native vegetation (19.5 percent VWC_{bottom}). However, cap type comparisons varied by year: soil VWC at the bottom of the soil-only caps was lower than all other cap types in 2005 (20.2 percent VWC) but greater in 2006 (22.7 percent VWC). VWC_{bottom} was greatest in RCRA cap types, especially when planted with crested wheatgrass (VWC_{bottom} = 22-23 percent).

Soil water "breakthrough" was considered to occur when VWC became greater than 28 percent at the bottom of a cap. Field capacity, as estimated from earlier reports (Anderson and Forman, 2003), is approximately 28 percent, and percolation below the bottom of the cap could occur at VWC_{bottom} greater then 28 percent VWC. Unfortunately we can not truly know if breakthrough occurred, without measuring VWC underneath the cap, thus we can only assess the "potential" for breakthrough here.

Table 3: Results of 4-way ANOVA comparison of volumetric water content at the greatest depth of measurement as affected by cap type (Cap), precipitation or irrigation regime (Precip), planting cover type (Veg), and year of measurement (Year). ($p<0.001$=*).**

Source	DF	Sum of Squares	F Ratio
Cap	3	1789.6	90.0^{***}
Precip	2	11511.3	868.4^{***}
Veg	1	3260.3	491.9^{***}
Year	4	3671.0	138.5^{***}
Cap*Veg	3	309.4	15.6^{***}
Cap*Precip	6	1880.9	47.3^{***}
Cap*Year	12	1286.5	16.2^{***}
Precip*Veg	2	219.5	16.6^{***}
Precip*Year	8	2601.1	49.1^{***}
Veg*Year	4	254.6	9.6^{***}

Subplots planted with native vegetation and receiving either ambient or supplemental summer irrigation did not exhibit any breakthroughs from 2002-2006 (Figure 11). No cap or vegetation type was invulnerable to breakthroughs under fall/spring irrigation, and breakthroughs occurred on at least one treatment in every year except 2002. The following factors were associated with a greater occurrence of a breakthrough among plots, in decreasing order of significance: i) having fall/spring irrigation, ii) having the soil-only cap type, and iii) having crested wheatgrass. Interestingly, plots with native vegetation that received summer precipitation had better water storage capacity and less of a tendency for potential breakthrough in years after the drought than non-irrigated plots. Subplots planted with crested wheatgrass had breakthroughs following drought years on caps of all types, even under ambient precipitation. RCRA cap types had the lowest frequency of breakthroughs of all cap types, probably due to runoff from the FML. In some cases when breakthrough was observed, there was still some soil water storage capacity in shallower depths of the soil profile which could store additional precipitation.

Degree of potential cap breakthrough was estimated by subtracting 28 percent (the estimated field capacity) from the percent VWC_{bottom} (Figures 12, 13, and 14). In general, all cap types receiving either ambient precipitation or especially summer irrigation had fewer and smaller (smaller VWC-28 percent) breakthroughs than did cap types receiving fall/spring irrigation. Cap types planted to native vegetation exhibited smaller breakthroughs, in addition to fewer breakthroughs.

The subplots reaching the greatest average degree of breakthrough were soil-only cap types planted with crested wheatgrass (VWC_{bottom} = 42 percent under ambient precipitation, 33 percent under summer irrigation, and 42 percent under fall/spring irrigation). In comparison, the maximum extent of breakthrough in a subplot planted with native vegetation was 36 percent VWC_{bottom}, in a soil-only cap type receiving fall/spring precipitation. Temporal duration of breakthroughs, indicated by the width of peaks showing breakthroughs in Figures 12, 13 and 14, were much greater for crested wheatgrass than native vegetation subplots. Thus, subplots with crested wheatgrass are not only more likely to have breakthroughs; they are less resilient and exhibit difficulty recovering from a breakthrough via ET. Soil-only plots also had broad breakthrough peaks, indicating slower recovery.

2.4 Relationships of water and plant cover

To determine the importance of variation in plant cover on PCBE plots from 2002-2006 to soil water depletion, ET values were calculated (Anderson and Forman 2002) and compared to cover within subplots (Figure 15). ET values for RCRA cap types were excluded as a result of un-quantified water lost as runoff from the FML that could be mistakenly attributed to ET. However, ET values for plots having breakthroughs were included because exclusion of these values would preclude the examination of wet conditions. Additionally, excluding ET values for plots experiencing

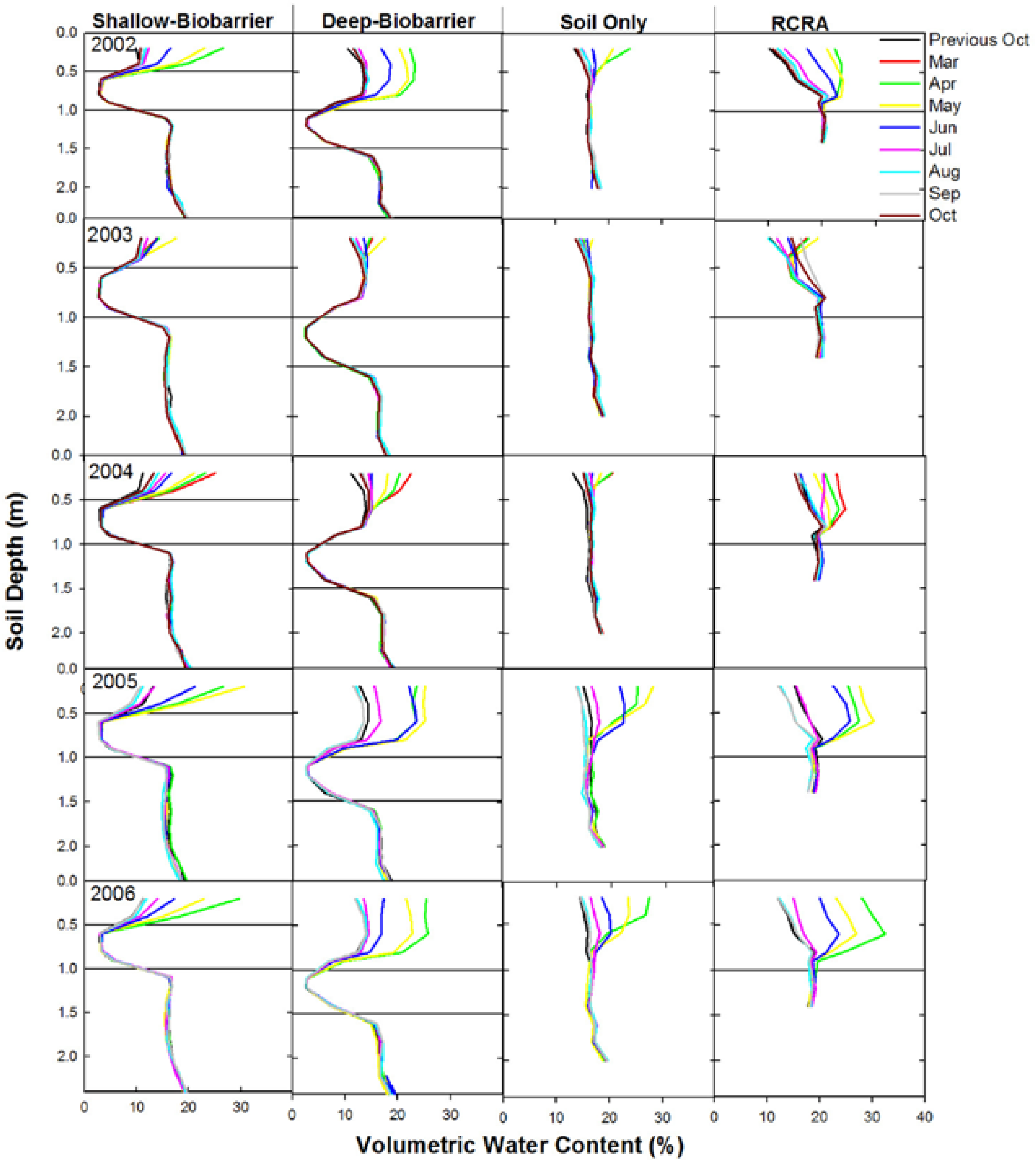


Figure 9: Representative soil moisture profiles for shallow-biobarrier, deep-biobarrier, soil-only, and RCRA cap types, receiving ambient precipitation and planted with native vegetation for 2002-2006. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Data are from subplots 8-3 (shallow-biobarrier), 9-5 (deep-biobarrier), 5-3 (soil-only) and 12-5 (RCRA) of the PCBE at INL. Graphs correspond to figures 9-12 and representative plots therein, in Anderson and Forman (2003). See statistics in Table 3.

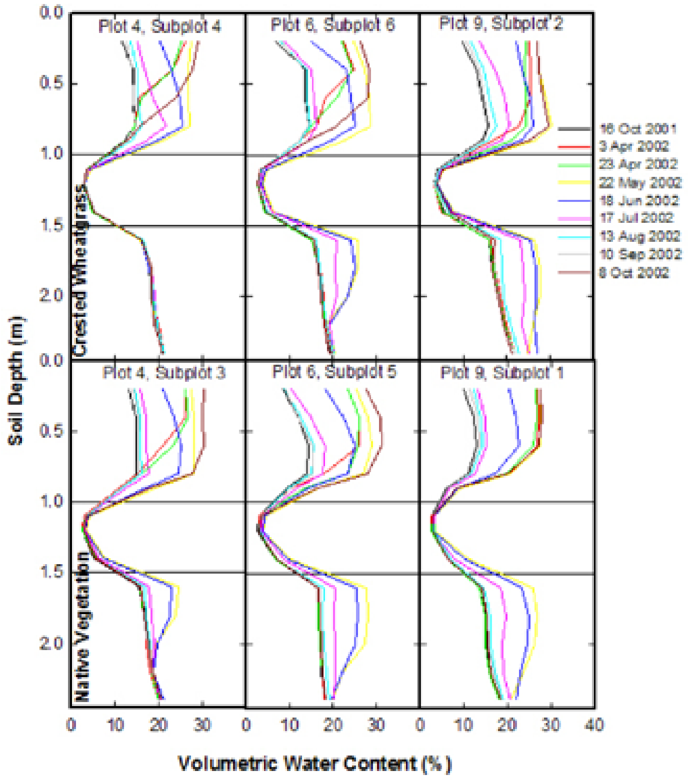


Figure 10: Soil moisture profiles in 2002 for all deep-biobarrier subplots receiving fall/spring precipitation. Crested wheatgrass replicates are shown in the upper panels; native vegetation replicates are shown in the lower panel. Each line depicts volumetric water content as a function of soil depth for a particular sampling date. Graph corresponds to figure 13 in Anderson and Forman (2003).

breakthrough would require the removal of data for all plots for these dates, leaving only 2002 data and eliminating the examination of the relationship between cover and ET. Total vegetative cover and calculated ET over all subplots, excluding the RCRA cap type, were positively correlated (Figure 15, r^2=0.24, F_{268}=84.11, p<0.0001). Plant cover and ET were positively related only in plots receiving fall/spring irrigation (Table 4).

ET values were compared among cap type (excluding the RCRA cap type and including breakthrough plots), precipitation regime, and vegetation cover type (Figure 16). Soil-only cap types, subplots receiving fall/spring irrigation, and subplots planted with native vegetation had the greatest mean ET values (335 mm, 448 mm, and 324 mm, respectively).

Total vegetative cover and cumulative precipitation from the beginning of the current water year until the date on which plant cover was sampled were positively correlated (Figure 17; r^2=0.23, F=105.8, p<0.0001). Significant positive correlations were also found within cap types, precipitation regimes, and vegetation types (Table 5). Having RCRA or shallow biobarrier caps, summer irrigation, and native vegetation enhanced the relationship of cover and precipitation.

3.0 Discussion

The 2002-2006 study period presented a unique opportunity to assess the resiliency of the PCBE caps to one of the primary long-term challenges to cap performance: resumption of community evapotranspiration as precipitation increases following extended drought. Patterns of plant cover and soil water depletion were mostly similar between the 2002-2006 study and 1994-2000 study, with some important exceptions including a greater occurrence of water accumulation at the bottom of the ET caps.

3.1 Soil Water and Breakthrough Tendency

During the 1994-2000 study, all four cap types performed satisfactorily under both ambient, summer, and fall/spring precipitation regimes, except for the RCRA cap type, which exhibited less water storage capacity and more breakthroughs under supplemental precipitation.

In 2002-2006 there appeared to be no potential for breakthrough in caps receiving either ambient precipitation or summer irrigation that had been planted to native vegetation. Fewer breakthroughs in native vegetation subplots under summer irrigation compared to ambient precipitation is surprising, given that this supplemental irrigation treatment adds substantial water to the soil profile. A possible explanation for this effect is that the regular water additions buffered the

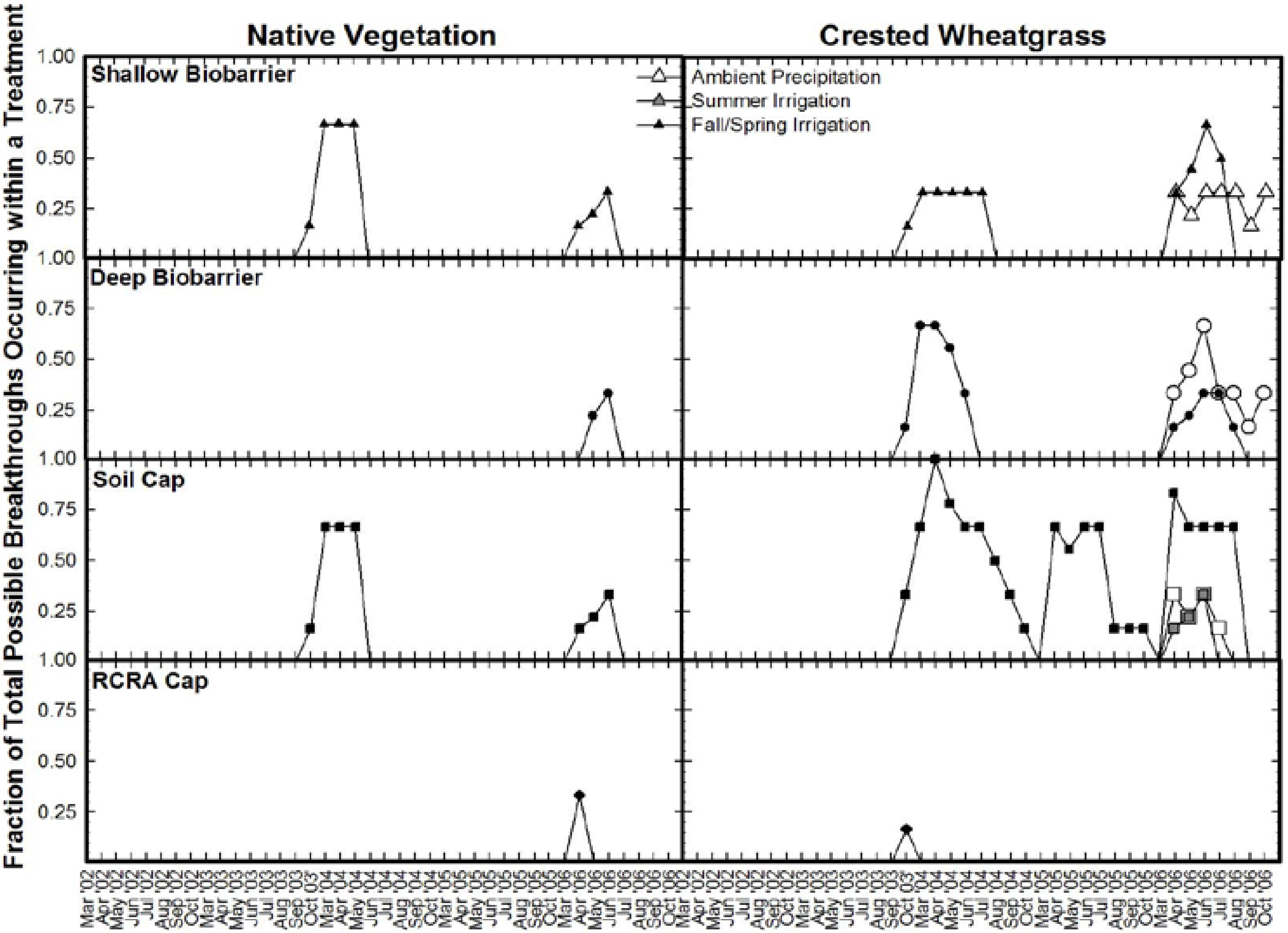


Figure 11: Fraction of the total number of possible (potential) breakthroughs, defined as volumetric water content greater than 28 percent at the bottom of the cap, for shallow-biobarrier, deep-biobarrier, soil-only, and RCRA cap types under ambient (open symbols), summer (gray symbols), and fall/spring (black symbols) precipitation regimes in native vegetation and crested wheatgrass subplots. We can only assess the possibility of breakthrough, and not whether breakthrough actually occurred, because VWC was not measured underneath the ET caps.

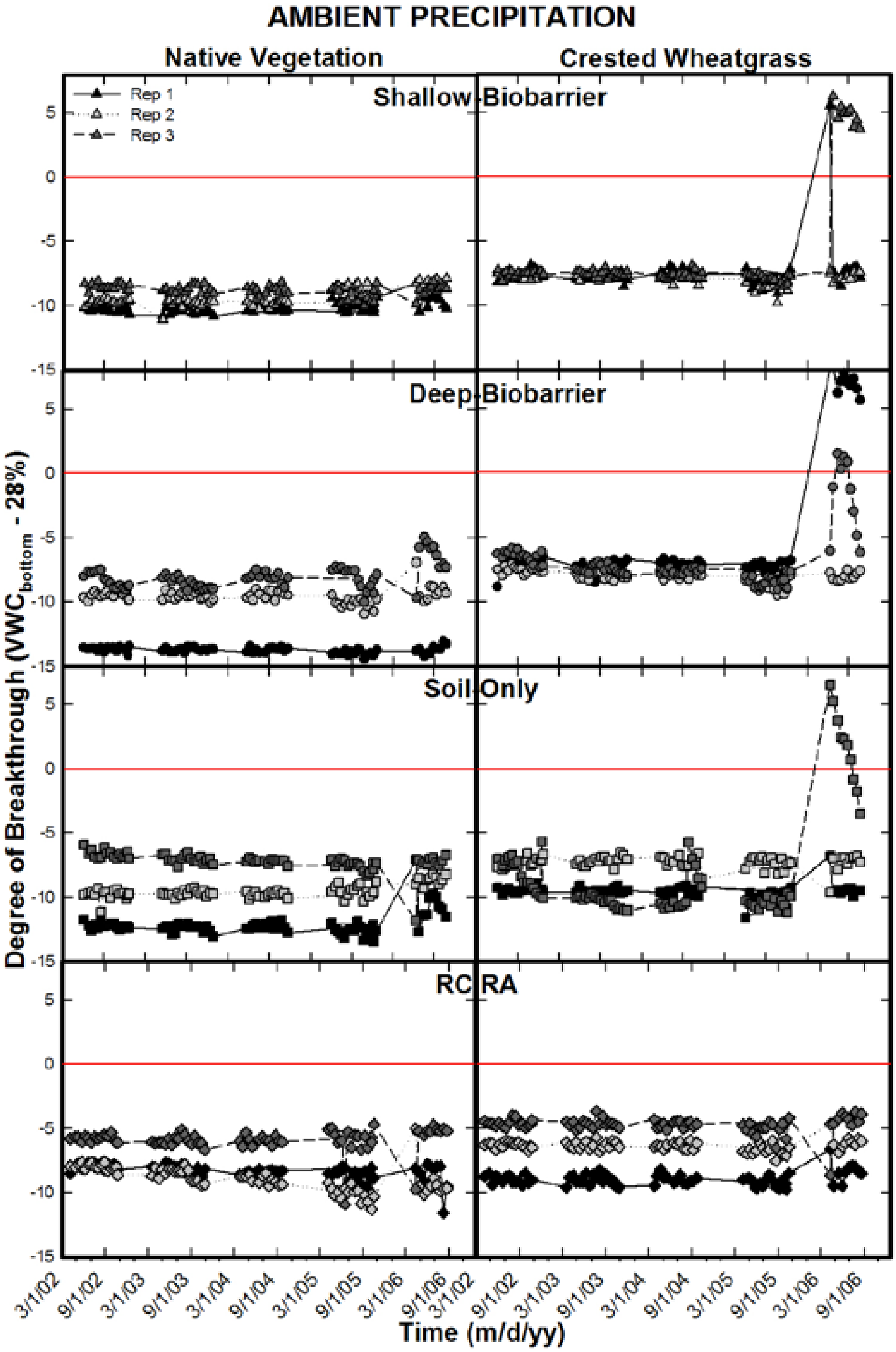


Figure 12: Degree of breakthrough for shallow-biobarrier, deep-biobarrier, soil-only, and RCRA cap types receiving ambient precipitation as calculated as the volumetric water content at the bottom of the cap minus 28 percent (field capacity). Symbols represent the three replicate plots (n=3) in each treatment combination.

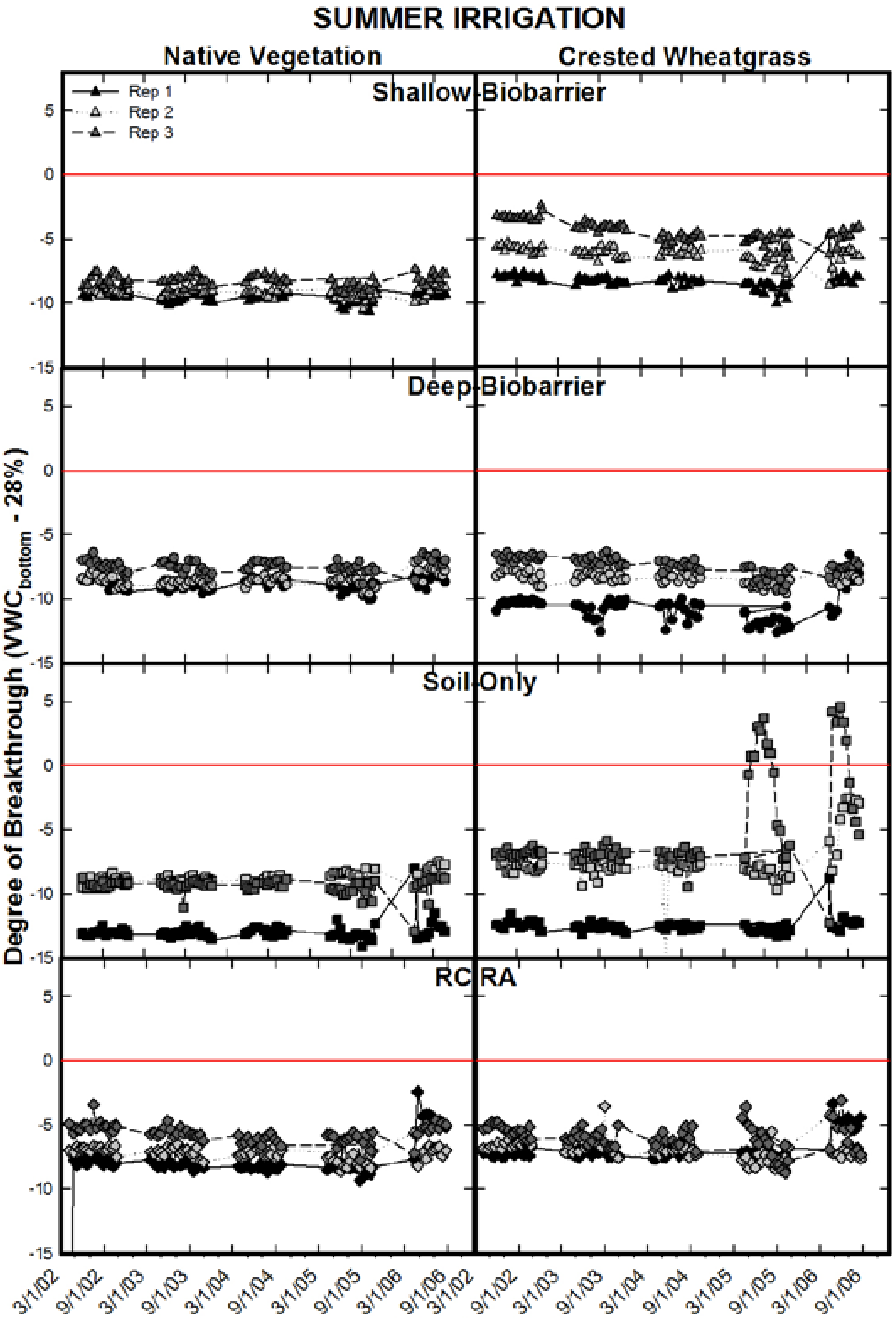


Figure 13: Degree of breakthrough for shallow-biobarrier, deep-biobarrier, soil-only, and RCRA cap types receiving summer irrigation as calculated as the volumetric water content at the bottom of the cap minus 28 percent (field capacity). Symbols represent the three replicate plots (n=3) in each treatment combination.

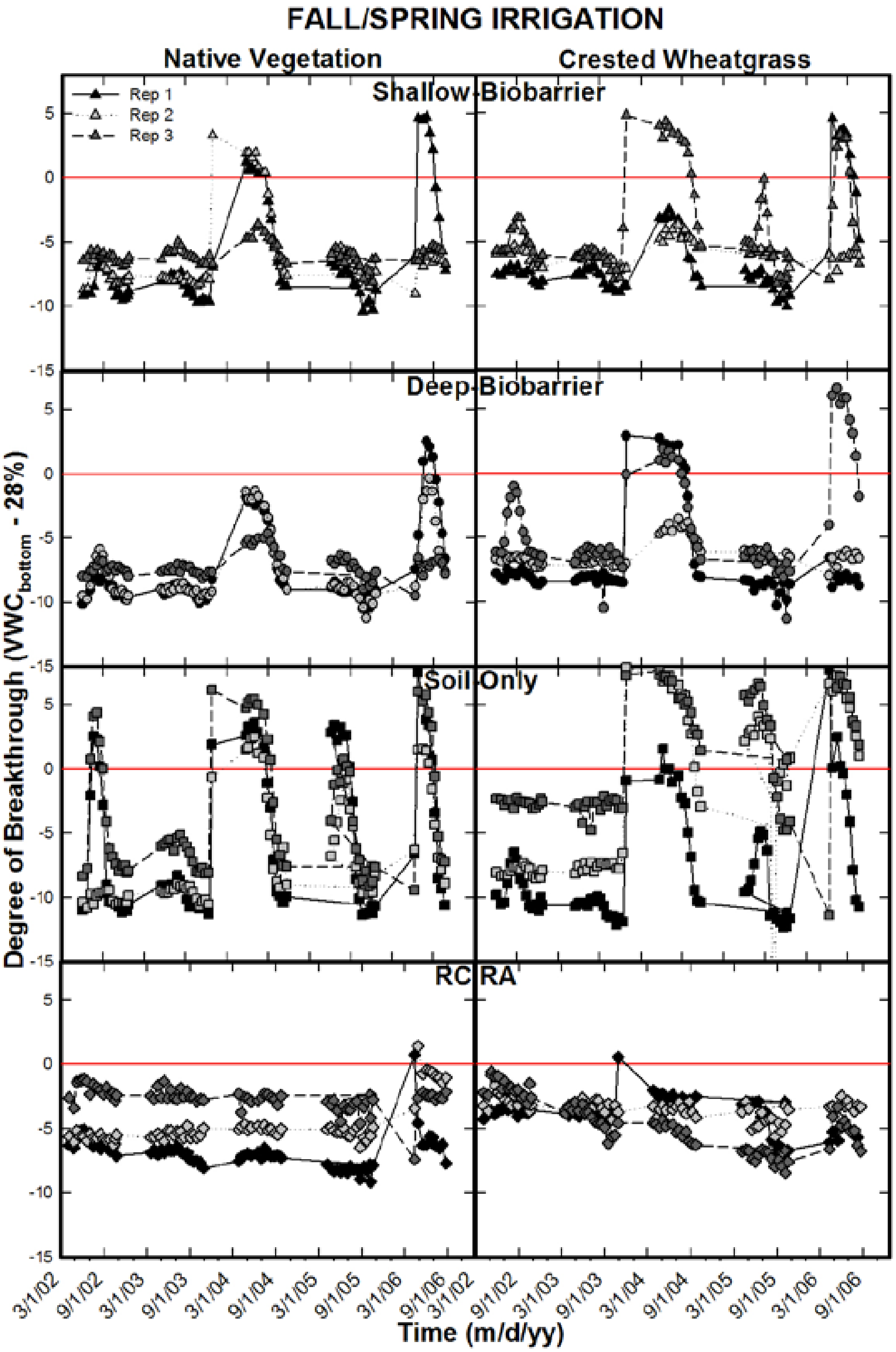


Figure 14: Degree of breakthrough for shallow-biobarrier, deep-biobarrier, soil-only, and RCRA cap types receiving fall/spring irrigation as calculated as the volumetric water content at the bottom of the cap minus 28 percent (field capacity). Symbols represent the three replicate plots (n=3) in each treatment combination.

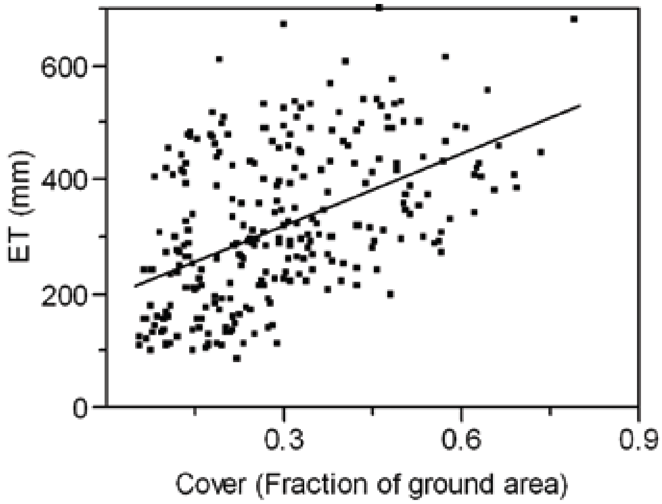


Figure 15: Relationship of plant cover and evapotranspiration (ET) of all subplots excluding RCRA cap types

Table 4: Results of correlations between evapotranspiration (ET) and cover for each cap type (excluding RCRA), precipitation or irrigation regime, and vegetation type ($p<0.05$=*, $p<0.01$=, $p<0.001$=***).**

Plot Type	Slope mm/%	r^2	F
Deep Bio-barrier	345.13	0.20	22.22***
Shallow Bio-barrier	371.98	0.25	28.71***
Soil-only	512.49	0.27	32.23***
Ambient precipitation	373.63	0.22	24.18***
Summer irrigation	259.24	0.29	35.31***
Fall/Spring irrigation	97.55	0.03	2.84
Native vegetation	605.24	0.42	95.81***
Crested Wheatgrass	636.09	0.25	42.98***

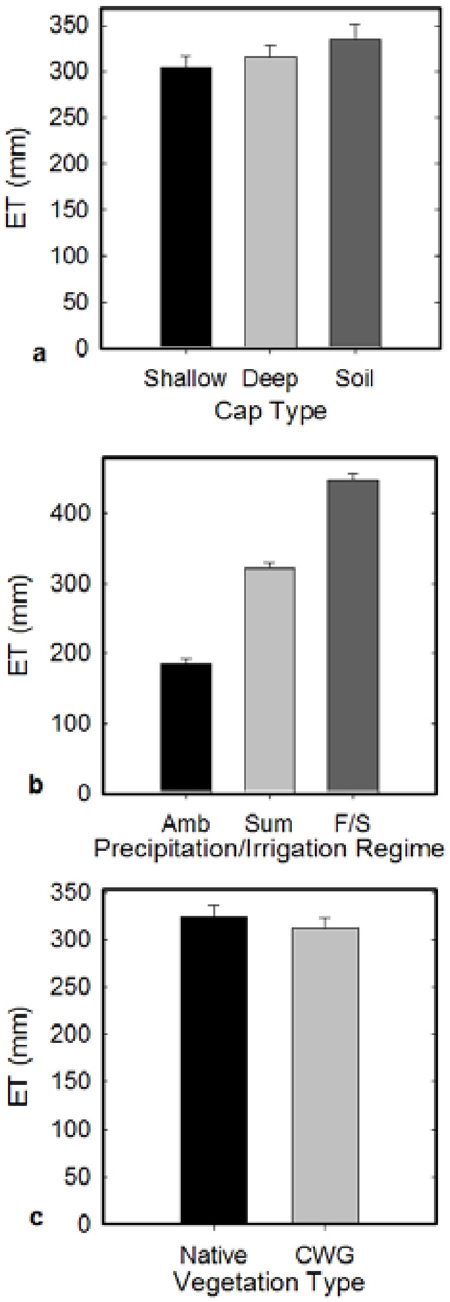


Figure 16: Calculated evapotranspiration (ET, mm) for each three cap types (a), three precipitation regimes (Amb=ambient precipitation, Sum=summer irrigation, F/S=fall/spring irrigation) (b), and two vegetation types (c) ± standard error. All calculations exclude RCRA plots.

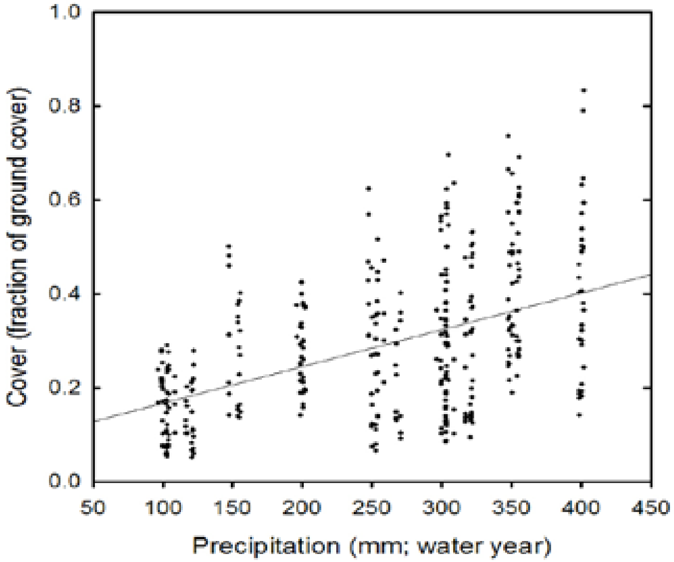


Figure 17: Relationship of plant cover and water year precipitation.

Table 5: Results of correlations between water year precipitation and cover as a function of cap type, precipitation or irrigation regime, and vegetation type ($p<0.05$=*, $p<0.01$=, $p<0.001$=***).**

Plot Type	Slope (%/mm)	r^2	F
Shallow-Biobarrier	0.00090	0.29	36.4***
Deep-Biobarrier	0.00073	0.19	21.2***
Soil-only	0.00060	0.15	15.2**
RCRA	0.00091	0.31	38.7**
Ambient Precipitation	0.00110	0.19	27.7***
Summer Irrigation	0.00150	0.20	30.1***
Fall/Spring Irrigation	0.00110	0.06	7.8**
Native Vegetation	0.00098	0.39	113.2***
Crested Wheatgrass	0.00059	0.27	65.8***

plant communities on ET caps from drought related effects, enabling these communities to sustain the ability to utilize greater amounts of available water. This effect has been reported for summer precipitation uptake by desert trees (Williams and Ehleringer 2000). Trees located in regions that normally receive summer precipitation were relatively more capable of taking up isotopically labeled water additions at midsummer. Williams and Ehleringer (2000) suggested that the ability to use summer precipitation was not only a function of historical patterns of precipitation, but the effect also tended to function in a threshold (on/off) fashion. The data reported here suggest that episodic drought followed by above average precipitation increases susceptibility to breakthrough. Ironically, watering ET caps during drought could conceivably avoid subsequent breakthrough even if irrigation is sustained as precipitation resumes following drought.

High levels of breakthrough with supplemental fall/spring irrigation could be due to low-temperature and phenological limitations to physiological water use during the fall and spring. This speculation is supported by the rather weak and only slightly positive correlation between cover and precipitation for subplots receiving fall/spring irrigation. Supplemental summer irrigation treatments led to slightly more plant cover than fall/spring irrigation. Future changes in precipitation simulated in the PCBE are very likely to be accompanied by warming patterns in future decades. Temperature effects on plant phenology and water use may be as important to soil water in ET caps as the abundance of precipitation. Assessments of fall/spring and summer warming (separately) are thus needed to make realistic predictions of ET cap performance in future decades, and could be assessed on the current PCBE using inexpensive, passive warming devices (e.g. Germino and Smith 1999).

RCRA and soil-only cap types had the least and greatest number of breakthroughs of all cap types for the 2002-2006 study, respectively. This is despite RCRA caps typically having the least amount of total vegetation cover. However, breakthroughs reported here for RCRA caps are more diagnostic of cap failure then are breakthroughs (or potential breakthroughs) reported for the other cap types. The presumption of cap failure for RCRA caps is based on the greatest depth of measurement, which is below the FML, and would thus be equivalent to water movement into interred wastes. Conversely, some degree of breakthrough is permissible in the shallow-biobarrier, deep-biobarrier, and soil-only cap types, according to EPA guidelines for alternative ET covers. The 1994-2000 study findings were nearly opposite in that the soil-only type appeared more effective at storing and returning soil moisture to the atmosphere than RCRA cap type. However, as Anderson and Forman (2003) noted, the shallow soils of the RCRA cap types are an inherent limitation to soil water storage, irrespective of whether RCRA soils become drier than in other caps during summer. Moreover, we do not know the extent of runoff on FML liners in RCRA caps which would require disposal.

In a comparison similar to the PCBE of soil-only and RCRA caps over 10 years at Los Alamos lab, Breshears et al (2005) also found slightly better performance of the RCRA design. One factor that could influence the greater tendency of breakthrough in soil-only caps during the 2002-2006 study is the development and sustained occurrence of hydraulic redistribution by plants. Sagebrush and other species are known to move soil water from relatively wet to drier locations (i.e. deeper in soil profile under surface-moist conditions; Richards and Caldwell 1987, Ryel et al. 2004). Progressive increases in rooting depth, especially during drought, could encourage deeper infiltration as well as redistribution of water directly by plants. Hydraulic redistribution would be most likely to occur in the deep soils of soil-only plots, where biobarriers are absent. Assessment of hydraulic redistribution could be achieved using isotopic tracers and finer scaled measurements of soil water.

Cap types in the 1994-2000 study planted with native vegetation were capable of returning a greater portion of soil moisture to the atmosphere than cap types planted with crested wheatgrass. Similarly, during 2002-2006, subplots planted with native vegetation generally had a greater water storage capacity and limited frequency and degree of potential breakthroughs than did subplots planted with crested wheatgrass. This consistent trend would suggest that subplots planted with native vegetation are more capable of maintaining sufficiently low VWC at the bottom of the cap than subplots planted with crested wheatgrass. In fact, the tendency for breakthrough to occur following drought in any cap type or precipitation regime having crested wheatgrass may indicate the unsuitability of this species for ET caps. Crested wheatgrass is no longer utilized for ET cap plantings at INL and its use should probably be carefully examined where waste burials occurs elsewhere in cold desert. Additionally, caps previously planted with crested wheatgrass could potentially benefit from native plantings.

3.2 Abundance of Cover: An Important Target for ET Caps Design?

Success of caps over long time periods that encompass variability in climate should be, to some extent, a function of the ability of plant cover to persist on the caps. Stability of ecosystem function is often correlated with a healthy and resilient plant community (Purvis and Hector 2000), but stability can also relate to sluggish acclimation of cover to increased precipitation. Native vegetation plots had significantly greater total vegetation cover, and exhibited significantly lower coefficients of variance (CV) than the crested wheatgrass subplots, from 2002-2006.

In attempting to determine possible causes of variability in cover, we examined relationships between cover and annual precipitation. Crested wheatgrass cover was less correlated to precipitation than native cover, so other factors, such as litter (plant detritus accumulation), may contribute to variability in crested wheatgrass cover (Anderson and Forman 2003). Greater variability in cover on RCRA caps could be related to negative effects of decreased water storage on the ability of plant cover to endure drought.

The abundance of plant cover in a plot was significantly, yet weakly correlated to the amount of soil water depletion in caps in all but the fall/spring irrigation treatment. However, percolation below the bottom of the caps for subplots receiving fall/spring irrigation probably misrepresents the change in soil water storage, which would subsequently effect ET calculations. We can only speculate about possible explanations for these findings, but the data indicate that generic abundance of plant cover is probably not an adequate target for cap design and construction goals. Candidate explanations for the weak relationships of plant cover and precipitation and soil water changes include i) positive effects of plant cover on water infiltration, ii) variation in physiological water use within and among species, and iii) hydraulic redistribution of water by plants on caps. Also, using soil water balance to estimate ET requires assumptions on the fate of soil water, and direct measures of ET (e.g. with gas exchange) could have stronger relationships to plant cover.

The stability of plant species composition in the PCBE plots was variable. Research indicates crested wheatgrass has an unusual potential to invade and eventually dominate adjacent native communities (Hull and Klomp 1966, 1967; Marlette and Anderson 1986). Results of the 2002-2006 study were not entirely consistent with the findings of these previous studies. Native species encroached upon subplots planted with crested wheatgrass to a greater degree than did crested wheatgrass encroach upon native vegetation subplots. The contrast between the 2002-2006 study and other research could potentially be a result of relatively small subplots and the heterogeneous mix of crested wheatgrass and native subplots within the larger PCBE landscape. Subplots within the PCBE probably have reciprocal influences due to seed transfer and other interactions. Other experiments on crested wheatgrass focused on situations having a single linear boundary between crested wheatgrass stands and adjacent native vegetation. In the PCBE study, small subplots of crested wheatgrass are randomly distributed throughout the main plots and are interspersed with subplots having the diverse mix of native species. A small patchwork design may afford native species a greater opportunity for dispersal, noted as an obstacle for establishment of native grasses (Marlette and Anderson 1986), and subsequent establishment within crested wheatgrass subplots. Alternatively, the biobarrier design may exclude small mammals, which are primary distributors of crested wheatgrass seed.

In conclusion, the most important finding here is that ET cap performance differed between the 1993-2000 and the 2002-2006 study periods. The effectiveness of the PCBE caps cannot be adequately addressed without long-term assessment. The current report indicates that none of the caps tested is capable of perfectly storing heavy fall/spring irrigation, particularly following drought cycles. It should be noted that supplemental fall/spring irrigation simulates extreme climatic conditions and is significantly greater than average precipitation. In addition, the EPA does allow a small amount of percolation to occur below the cap for alternative cap designs. Supplemental summer irrigation, however, appeared to improve cap performance, particularly following drought. Incorporating summer irrigation into cap design may enhance long-term viability of ET caps because benefits of enhanced ET following drought out-weigh potential costs due to water additions intended to "enhance" the community. Timing of precipitation events and temperature effects on soil water in ET caps may be as important as precipitation, and should thus be assessed. Cover type critically affects ET cap performance, to the extent that crested wheatgrass may be unsuitable for ET cap design. Three final research needs for ET caps are evident: i) variation in physiological water use among species and seasons within caps (i.e. timing of precipitation events and temperature effects), ii) considerations of how plants might alter soil water budgets aside from direct uptake of soil water, and iii) direct measures of cap ET.

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