Root Growth in Alternative Soil/Vegetation Covers at Rocky Mountain Arsenal

Project Report

Cynthia S. Brown and Khishigbayar Jamiyansharav

Department of Bioagricultural Sciences and Pest Management

1177 Campus Delivery
Colorado State University
Fort Collins, CO 80523-1177
(970) 491-1949

Table of Contents

Executive summary 3

Introduction 4

Methods 5

- Sample collection 5
- Root washing 5
- Root scanning 6
- Root drying and weighing 7
- Data analysis 7

Results 9

- Root Length Density (RLD) 9
- Mass per volume (MPV) 12
- Average diameter (AD) 14
- Vegetation cover 17

Discussion 18

Literature cited 20

Appendix 21

Executive Summary

The three lysimeters of Shell Disposal Trenches (SDT) Resource Conservation and Recovery Act (RCRA)-equivalent cover at Rocky Mountain Arsenal (RMA) exceeded the maximum amount of percolation allowed under the compliance standard in spring 2015 and 2016. The Integrated Cover System RCRA-equivalent (ICS) cover continued to meet the compliance standard. We assessed plant root characteristics in the two cover types and a natural site in an effort to understand the underlying cause of excessive percolation in the SDT cover. Three 4 foot soil cores were collected near each of three lysimeters in each cover type at RMA. Another three soil cores were collected from a native area on the Rocky Mountain Arsenal National Wildlife Refuge. Soil cores were divided into 6 inch samples, soil was washed from the roots in each sample, and roots were analyzed using an optical scanner and image analysis software. Root length density (RLD, length of root per unit volume of soil), mass per volume (MPV, dried root weight per volume of soil), and average diameter (AD) of the roots were measured in each sample.

There were two differences in root characteristics between the two cover types. First, RLD in the SDT cover was less than the ICS cover at the deepest depth (43-48 inches). Second, RLD was greater in the SDT cover than ICS cover at the next shallowest depth (37-42 inches). These two differences are likely due to a 6 inch layer of compacted soil in the SDT cover that was created as part of its construction and was not included in the ICS cover design. We did not detect differences between the covers in distribution of MPV or AD with depth. Nor did we detect differences in variation of these root characteristics (coefficient of variation [CV] and deviation from the mean [residual]) that would indicate differences in root heterogeneity between the two cover types.

The two cover types were more similar to each other than to the native site. Both cover types had greater RLD at the shallowest depth and greater total RLD than the native site. The SDT cover had greater AD than the natural site; the ICS cover was not different from either.

Our results provide little evidence for differences in plant development, in particular root characteristics, causing differences in percolation between SDT and ICS covers. Exploration of differences in the species composition of the plant communities may provide additional insights. However, the physical features that affect movement of water through plants and soil may not be appreciably different among the herbaceous species that occur on the covers of RMA.

Introduction

Plant root development was assessed in soils of two types of Resource Conservation and Recovery Act (RCRA)-equivalent covers on Army retained Land at the former Rocky Mountain Arsenal (RMA) and one native area on the Rocky Mountain Arsenal National Wildlife Refuge (RMANWR). The two RCRA-equivalent covers evaluated were the Shell Disposal Trenches (SDT), which was constructed over the former RMA disposal site in 2006 and 2007 (Navarro 2015a), and the Integrated Cover System (ICS), which is comprised of four contiguous RCRA-equivalent covers that were constructed between 2007 and 2008 (Navarro 2015a). The SDT cover had vegetation cover for 8 years and the ICS covers for 6 years at the time roots were sampled for this project.

The cover systems have lysimeters installed to measure the amount of water that percolates through them. The SDT cover has three lysimeters (001, 002, and 003) and the ICS cover have an additional 12 lysimeters (15 lysimeters total). The maximum amount of percolation allowed under the compliance standard is 1.3 mm/year (rolling 12-month average). This project was developed in response to all three lysimeters in the SDT cover coming out of compliance with the percolation performance standard in May and June of 2015 and 2016, while the lysimeters of the ICS covers collected little or no percolation water. The Army is obligated to investigate the cause of excessive percolation, develop a plan to correct the condition, and to make the necessary modifications to the cover to ensure compliance with the standard.

The SDT cover was the first to be designed and constructed at RMA. The design was refined for construction of the ICS cover. Differences in percolation between the two cover areas may be due to differences in construction methods either directly or indirectly through their influence on the growth of plants aboveground or belowground, or both.

Plants serve as biological pumps that remove water from the soil through transpiration, thus, decreasing the amount entering layers below their roots. Limitations to plant growth aboveground would reduce the surface area available for transpiration, thus, reducing the amount of water removed from the soil profile. Limitations on root growth would reduce the ability of plants to thoroughly explore the soil profile vertically and horizontally, thus, their capacity to remove water from the soil through transpiration, which could lead to increased percolation.

Decomposed plant roots can also create physical channels through the soil that serve as conduits for water to deeper depths. Larger diameter roots are more likely to result in such channels.

The purpose of this project is to (1) identify whether there are differences in plant root development between the SDT and ICS covers and to (2) compare plant root development in the cover systems to root development in native grassland.

Methods

Sample collection

Soil core samples were collected near lysimeters that have exceeded the annual percolation compliance standard, which are located in the Shell Disposal Trenches (SDT) cover and near lysimeters with similar orientation that have not exceeded the annual percolation standard in the Integrated Cover Systems (ICS) area. Additionally, a Native Site (NS) on the Rocky Mountain Arsenal Wildlife Refuge (RMANWR) located in the northwest quadrant of Section 33, was selected as reference to a naturally occurring shortgrass prairie. Lysimeter 001, 002 and 003 were sampled from the SDT site and Lysimeter 004, 007 and 015 from the ICS site. ICS lysimeters were selected based on slope aspect and slope position to be similar to SDT lysimeters. Lysimeters 001 and 007 are on the north aspect at the toe of the slope. Lysimeters 002 and 015 are on the north aspect at the top of the slope. Lysimeters 003 and 004 are on the south aspect at the toe of the slope. Three soil cores were collected adjacent to each lysimeter and from NS to address vegetation and soil variability. One quality control core was also collected from near Lysimeter 003.

Each soil core was four feet long and was divided into eight samples, each 6 inches long. In some cases, the core was slightly less than 4 feet long, which resulted in the deepest sample being less than 6 inches. More information on the sampling site locations and descriptions can be found in the Sample and Analysis Work Plan, Revision A (Navarro 2015b). Samples for root analysis were transported to Colorado State University (CSU) Department of Bioagricultural Sciences and Pest Management (BSPM) on January 13th, 2016. The 22 soil cores (176 samples) were stored in a freezer at Dr. Cynthia Brown's laboratory at CSU until processing and analysis.

Root washing

Root washing took place at CSU greenhouse facilities, where we had access to water and the appropriate drainage system. Soil samples were transferred from the freezer to the refrigerator at least 2 days before washing to thaw them. Re-sealable plastic bags were pre-labeled according to the Site ID, top depth and bottom depth, as listed in the Soil Sample Chain of Custody Record. Roots were cleaned using repeated water rinses, soaking and agitation as needed to remove soil adhering to the roots. Roots were recovered by passing the soil-water solution through 2mm fine screen mesh. The remaining organic debris was removed from the clean roots by hand using tweezers. Roots that remained on the screen mesh were washed and placed in the pre-labeled plastic bags submerged in water and stored in a refrigerator for up to 5 days until scanning. We took pictures of the soil samples before and during the root washing to observe the soil color and characteristics in case this information may explain differences in rooting patterns among samples. Sample photos are included in Figure 1 and all other photos are included in the electronic appendices (see files provided).

a) b)

Figure 1. Photos taken a) before and b) during soil washing process

Root scanning

Root scanning took place at Dr. Cynthia Brown's laboratory at CSU. The clean roots were scanned using WinRHIZO Regular LA2400 System for automatic washed root analysis (Regent Instruments, Inc., Quebec City, Quebec, Canada; Image Analysis for Plant Science available at: http://www.regentinstruments.com/assets/winrhizo_about.html. Assessed on 09/23/2015).

WinRhizo is fast and easy to operate (Arsenault et al. 1995) and estimates the length of root in each sample for different root diameter size classes. The scanner was connected to a desktop computer. The scanner system is shown in Figure 2. Roots were floated in water in clear, plexiglass boxes of different sizes (Regent Instruments, Inc.) for scanning. The largest plexiglass box is shown in Figure 2.

Figure 2. WinRHIZO Regular LA2400 System.

Clean roots were placed in the smallest clear plexiglass box (10 cm x 15 cm) with water and distributed as evenly as possible. If the roots were too crowded, they were transferred to a box large enough to accommodate the sample (15 cm x 25 cm; 20 cm x 30 cm; 30 cm x 40 cm). Whenever larger boxes were used, the sample was scanned 2-3 times and the average was used in the dataset. 400 dpi was used for the best root imaging as recommended by the WinRHIZO manual (WinRHIZO 2016). The image and data were reviewed for quality after each scan, and the scan was cancelled and repeated, if necessary. Images were saved with and without analysis as shown in Figure 3.

a) b)

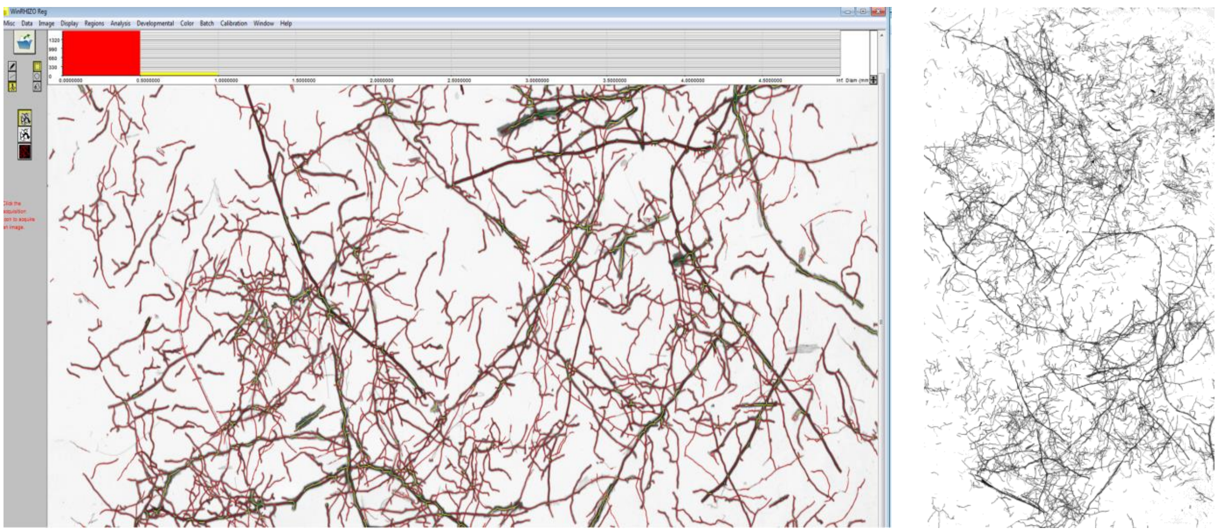


Figure 3. Root scanning images a) with and b) without analysis.

All images were stored as tiff and bitmap files and included in the electronic appendices (see files provided).

Root drying and weighing

After scanning, the roots were dried in the oven at 60 °C (24-48 hours) and weighed on a top-loading balance. Four significant digits beyond the decimal point were used due to very small amounts of roots in the deepest soil core samples. After weighing, each sample was placed in a separate coin envelope labeled with the sample identification information for long-term storage.

Data analysis

Root length density (length of root per volume of soil), mass per volume (dried root weight per volume of soil), and average diameter for each depth were analyzed to evaluate differences between the sites. One-way analysis of variance (ANOVA) repeated measures models with site (SDT, ICS, NS) as the independent variable were used. Depth was the repeated measure (within factor), and response variables were root length density (RLD), mass per volume (MPV) and average diameter (AD). A significant site by depth interaction ($p<0.05$) indicates that the response variable differed by depth among the sites. When this was the case, one-way ANOVA was conducted for each depth separately with site type as the independent variable. For the repeated measures

ANOVA, if Mauchly's test for sphericity was significant or if it was not possible to conduct Mauchly’s test, then Greenhouse-Geisser adjusted p-values were used to compensate for lack of sphericity. Differences among the site types in variation or heterogeneity of the response variables were investigated by calculating coefficients of variation (CV; standard deviation/mean) and absolute value of the residuals (observed-mean) for each response variable. One-way ANOVA was conducted on these measures of variation as described above. In addition, vegetation cover data for functional groups from the vegetation cover monitoring report (2015 vegetation cover and frequency summaries provided by Navarro Research and Engineering, Inc.) were pooled and analyzed using one-way ANOVA of mean absolute cover for grass, forb and total vegetation cover. Tukey-Kramer Honestly Significant Difference was used to identify which means were different from one another when an effect was significant in the ANOVA. JMP Pro12 (SAS Institute Inc. 2015. Cary, NC, USA) statistical software was used for all analyses.

Results

Root Length Density (RLD)

Repeated measures analysis of RLD showed a significant site by depth interaction (p<0.0001), which indicates that RLD at different depths depends on the site. Therefore, one-way ANOVA for each depth separately with site as the independent variable was conducted to determine which sites were different at each soil depth (Figure 4).

At the shallow depth (0-6 inches), ICS had significantly higher RLD (p<0.02) than NS but not significantly higher than SDT. SDT did not differ significantly from ICS and NS, but SDT and ICS tended to have higher RLD than NS at all depths, except at the deepest depth (43-48 inches. At the deepest soil depth (43-48 inches), SDT had significantly lower RLD than ICS (p<0.02) but not significantly lower than NS.

At the 37-42 inch soil depth, SDT had significantly higher RLD (p<0.03) than NS but not significantly higher than ICS.

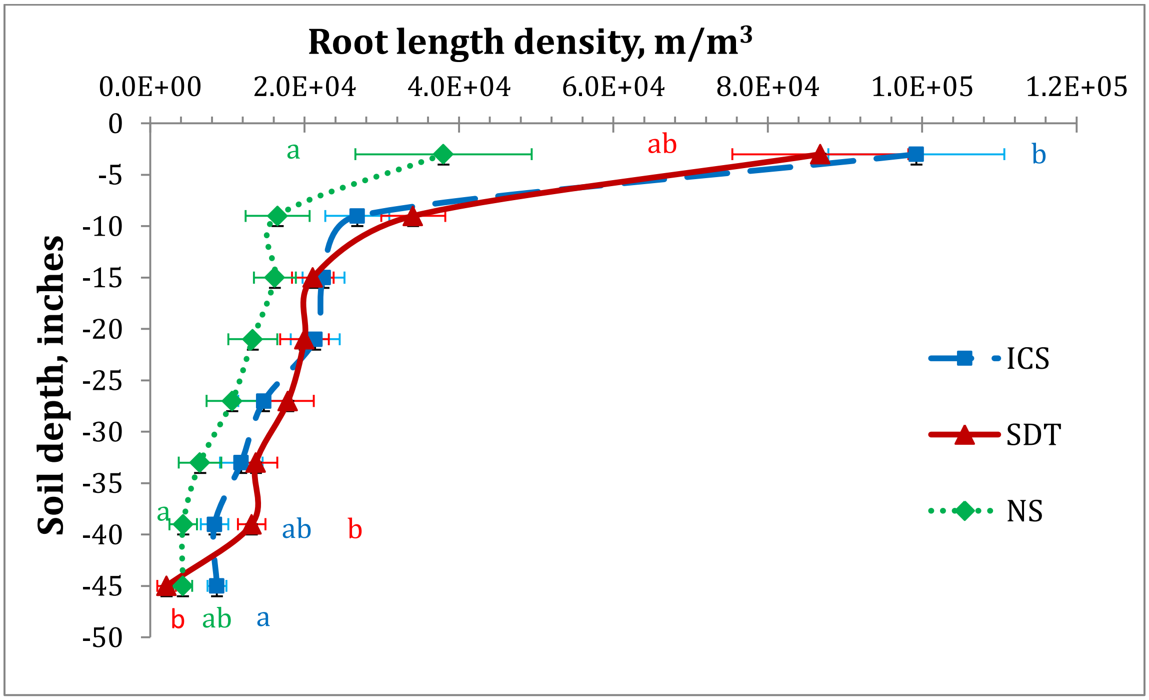


Figure 4. Root length density (RLD) by soil depths at different sites. Significant differences at P<0.05 level are indicated by different letters. ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site.

Total RLD in ICS and SDT were not significantly different from each other, but they had significantly higher total RLD (p<0.01) than NS. The total RLD for each site was 213 km/m^3 at ICS, 209 km/m^3 at SDT and 110 km/m^3 at NS. NS had nearly 50% less RLD than the cover sites.

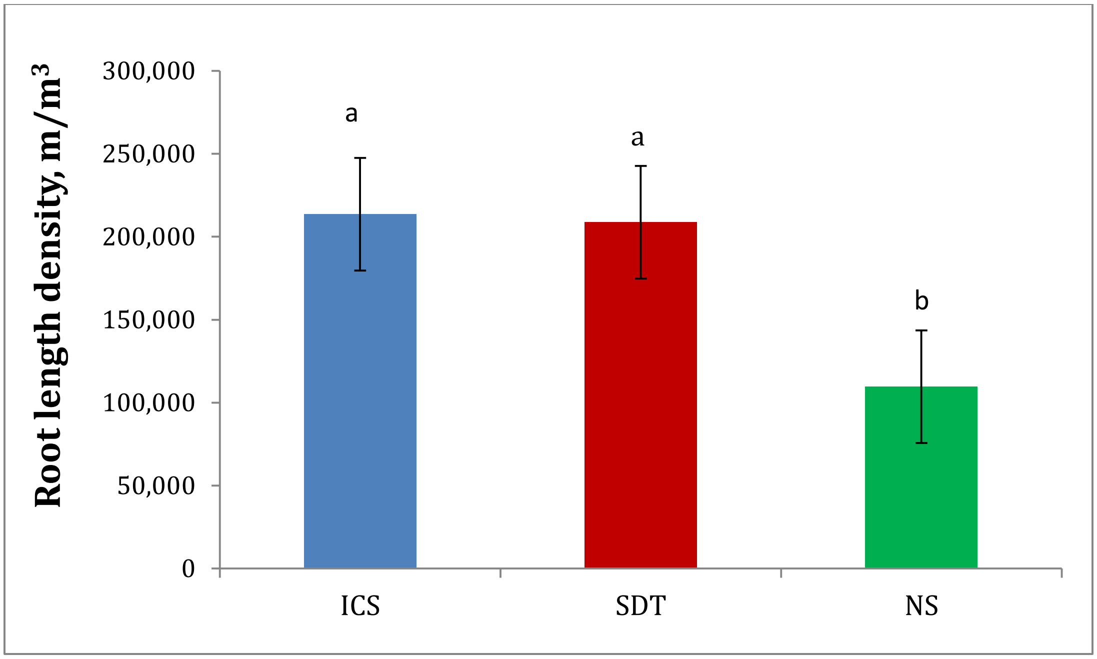


Figure 5. Total root length density (RLD) at different sites. Significant differences at $P<0.05$ level are indicated by different letters. ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site.

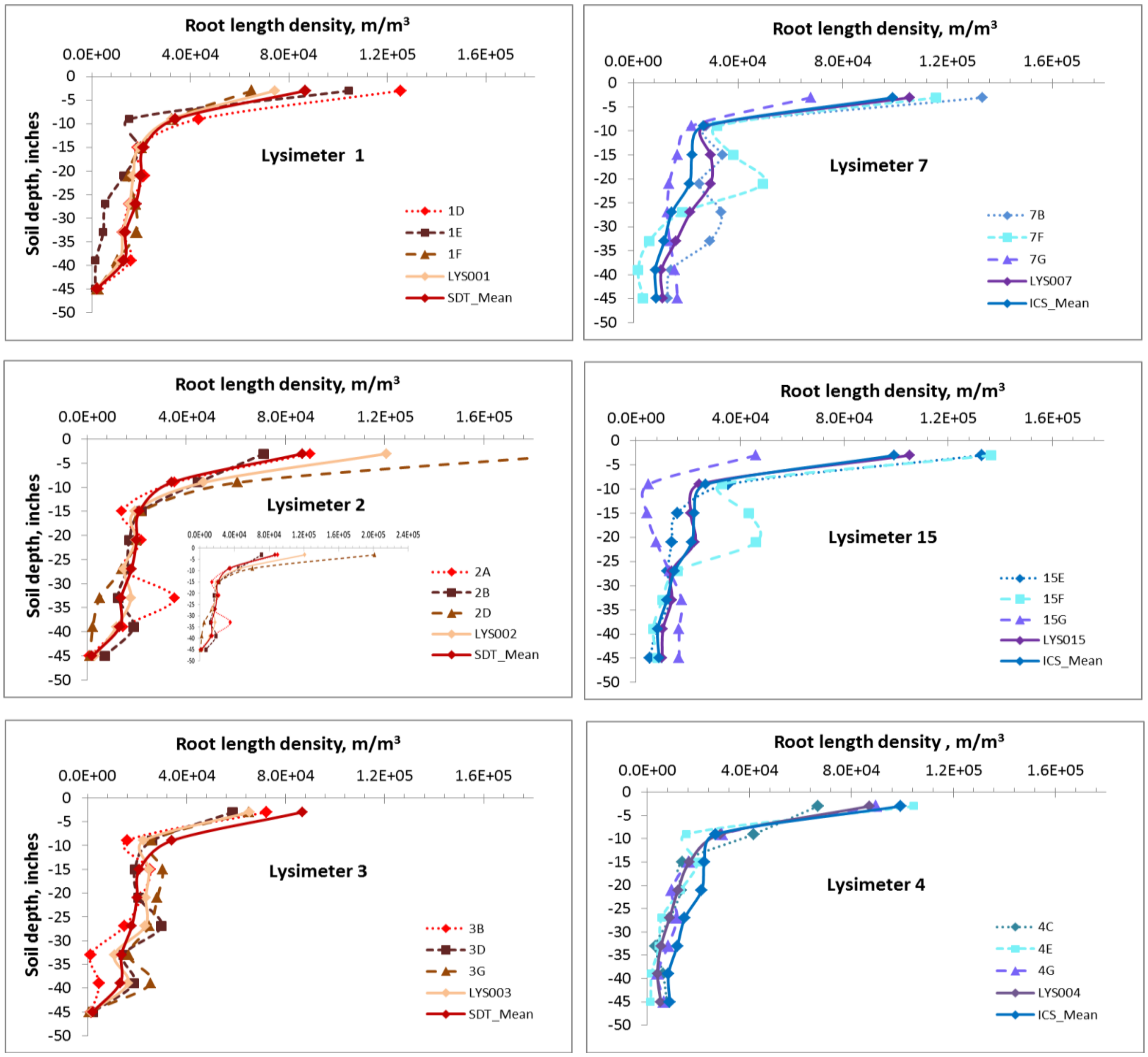
RLD within sites for each soil core

The graphs in Figure 6 facilitate comparison of RLD for each soil core across depths within sites. The graphs represent three soil cores from each lysimeter at ICS and SDT sites, and three soil cores from NS. Graphs for ICS and SDT sites have two means: one for the lysimeter (mean of three cores) and one for the site (ICS or SDT, mean of nine cores). NS has one mean for the three cores collected.

ICS soil cores had similar range of RLD for all soil cores (Figure 6). SDT also had a similar range of RLD for all cores except core 2D. This soil core had exceptionally high RLD at the shallow depth. The rest of the depths of this soil core had a similar range of RLD as the others. NS soil cores were similar to each other.

a) SDT Cover Lysimeter

b) Corresponding ICS Lysimeter



c) Native site

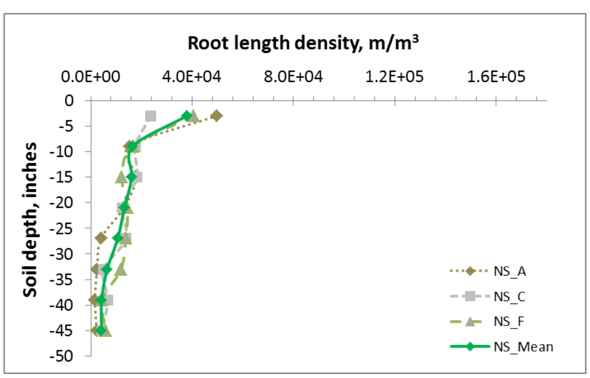


Figure 6. Comparison of root length density (RLD) for each soil core within sites: a) SDT-Shell Disposal Trenches. Inset graph shows all data points, including the outlier (RLD =201,240 m/m³) core 2D b) ICS-Integrated Cover System c) NS-Native Site. Lysimeters 001 and 007 are on the north aspect at the toe of the slope. Lysimeters 002 and 015 are on the north aspect at the top of the slope. Lysimeters 003 and 004 are on the south aspect at the toe of the slope.

RLD Coefficient of variation and absolute value of residuals
We analyzed coefficient of variation and absolute value of the residuals to investigate the variation and heterogeneity of the RLD. We detected no differences in these metrics that would indicate greater heterogeneity in one site than another (Table 1).

Table1. Summary of the analyses of the coefficient of variation and absolute value of the residuals for root length density (RLD) (num – numerator degrees of freedom; den – denominator degrees of freedom).

Response variable	Site	Mean ± SEM	Site		Site * depth	
			F (num, den)	p	F (num, den)	p
RLD coefficient of variation, %	ICS	48.6 ± 7.7	1.05 (1, 4)	0.364	1.49 (2.7, 10.9)	0.273
	SDT	40.8 ± 9.8				
RLD |residuals|, km/m³	ICS	4.4 ± 0.7	0.53 (1, 4)	0.51	5.46 (1.4, 5.6)	0.055
	SDT	1.7 ± 0.7				

Mass per volume (MPV)

Repeated measures analysis of MPV showed no significant site by depth interaction ($p<0.68$), which indicates that MPV at different depths did not depend on the site (Figure 7). Total MPV in ICS (3,845 ± 106), SDT (5,017 ± 776) and NS (2,511 ± 1188) were not significantly different from each other.

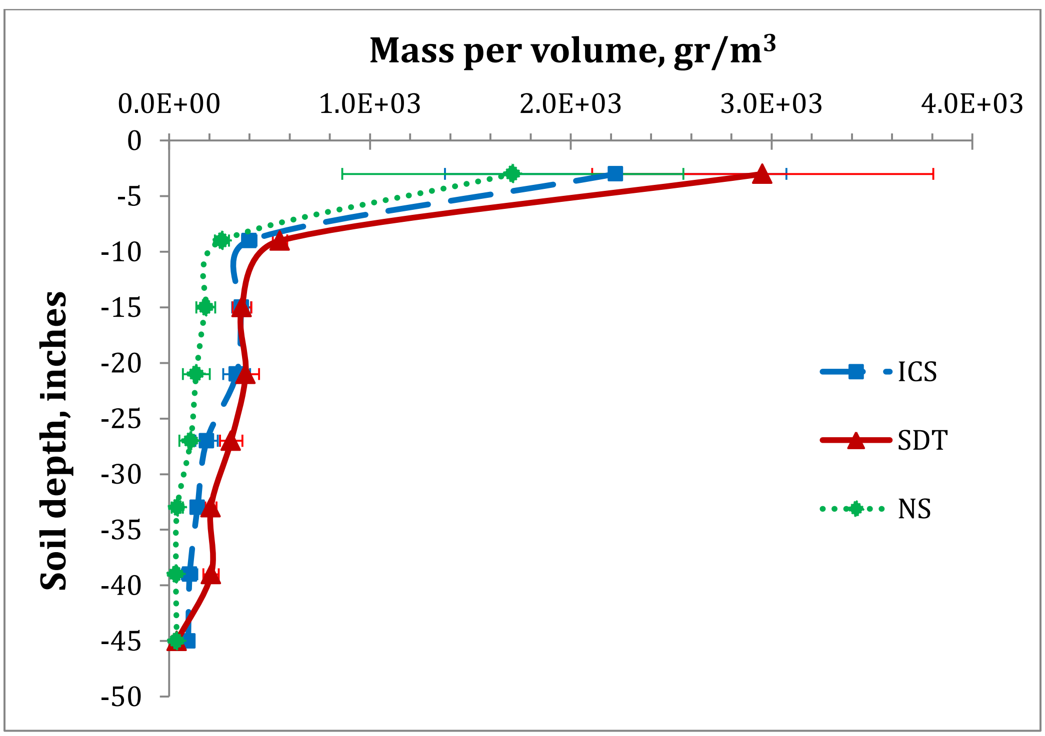


Figure 7. Mass per volume (MPV) at different soil depths at different sites. ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site.

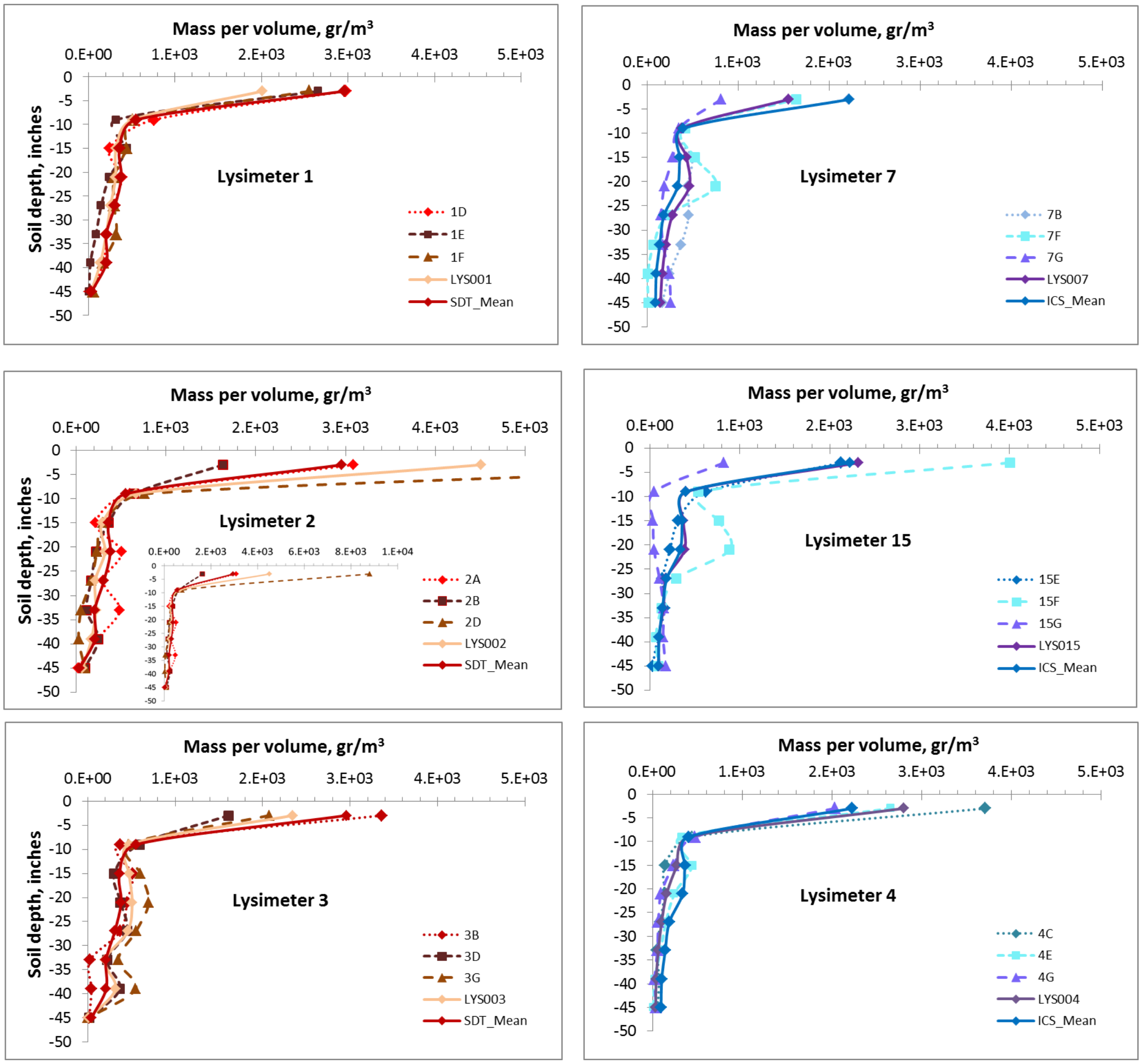
MPV within sites for each soil core

The graphs in Figure 8 facilitate comparison of MPV for each soil core across depths within sites. The graphs represent three soil cores from each lysimeter at ICS and SDT sites, and three soil cores from NS. Graphs for ICS and SDT sites have two means: one for the lysimeter (mean of three cores) and one for the site (ICS or SDT, mean of nine cores). NS has one mean for the three cores collected.

ICS soil cores had similar range of MPV for all soil cores (Figure 8). SDT also had similar range of MPV for all cores except core 2D. This soil core had exceptionally high MPV at the shallow depth. The rest of the depths of this soil core had a similar range of MPV as the others. NS soil cores were similar to each other.

a) SDT Cover Lysimeter

b) Corresponding ICS Lysimeter



c) Native Site

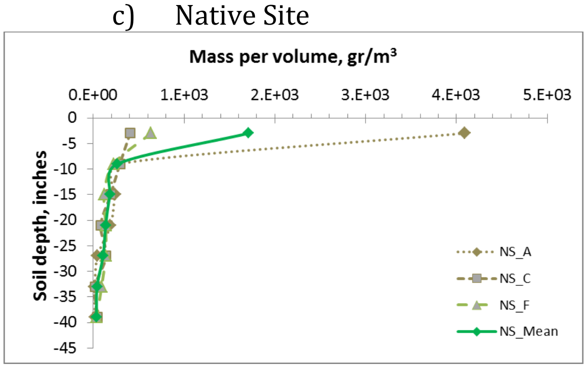


Figure 8. Comparison of mass per volume (MPV) for soil cores within sites: a) SDT-Shell Disposal Trenches. Inset graph shows all data points, including the outlier (MPV =8,797.6 gr/m³) core 2D b) ICS-Integrated Cover System c) NS-Native Site. Lysimeters 001 and 007 are on the north aspect at the toe of the slope. Lysimeters 002 and 015 are on the north aspect at the top of the slope. Lysimeters 003 and 004 are on the south aspect at the toe of the slope.

MPV coefficient of variation and absolute value of the residuals
Coefficient of variation and absolute value of the residuals were analyzed to investigate the variation and heterogeneity of MPV. No differences in these metrics that would indicate greater heterogeneity in one site than the other were detected (Table 2).

Table 2. Summary of the analyses of the coefficient of variation and absolute value of the residuals for mass per volume (MPV) (num – numerator degrees of freedom; den – denominator degrees of freedom).

Response variable	Site	Mean ± SEM	Site		Site * depth	
			F (num, den)	p	F (num, den)	p
MPV coefficient of variation, %	ICS	56.1 ± 9.0	0.98 (1, 4)	0.378	2.29 (1.6, 6.4)	0.185
	SDT	48.9 ± 8.8				
MPV |residuals|, gr/m³	ICS	103.5 ± 50.3	2.43 (1, 4)	0.194	3.29 (1, 4.2)	0.142
	SDT	183.5 ± 122.5				

Average diameter (AD)

Repeated measures analysis of AD showed no significant site by depth interaction ($p<0.37$), which indicates that AD at different depths did not depend on the site (Figure 9).

The mean of AD across all depths in SDT was significantly higher ($p<0.03$) than in NS. The mean of AD across all depths in ICS was not significantly lower than SDT and not significantly higher than NS (Figure 10).

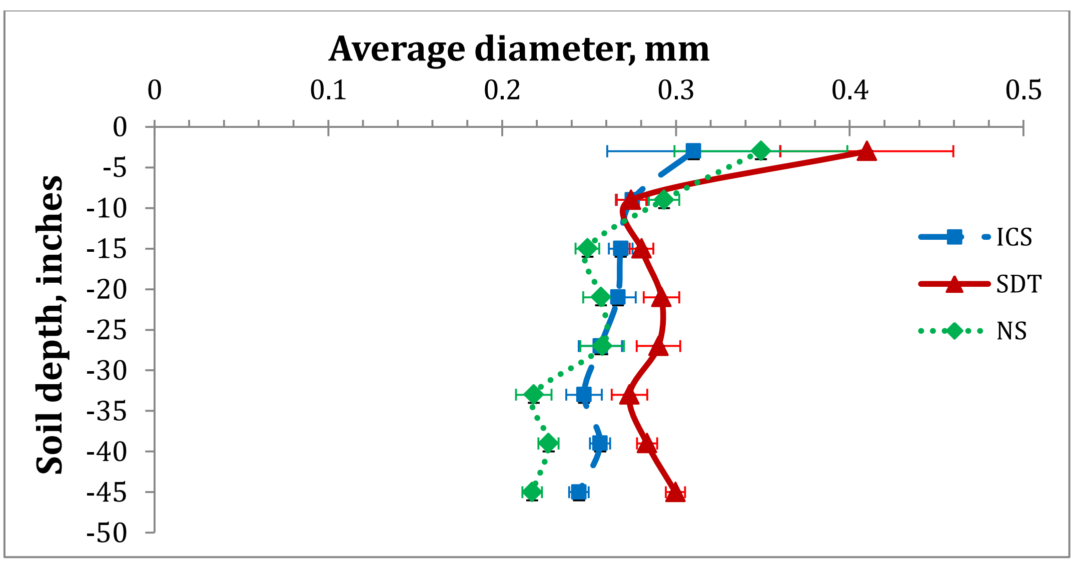


Figure 9. Average diameter (AD) across soil depths at RMA sites. ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site.

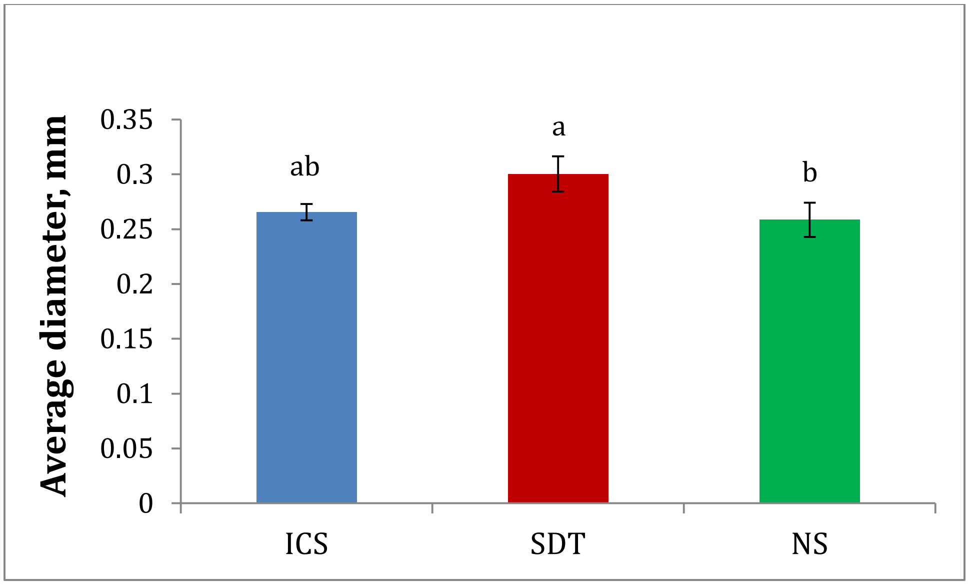
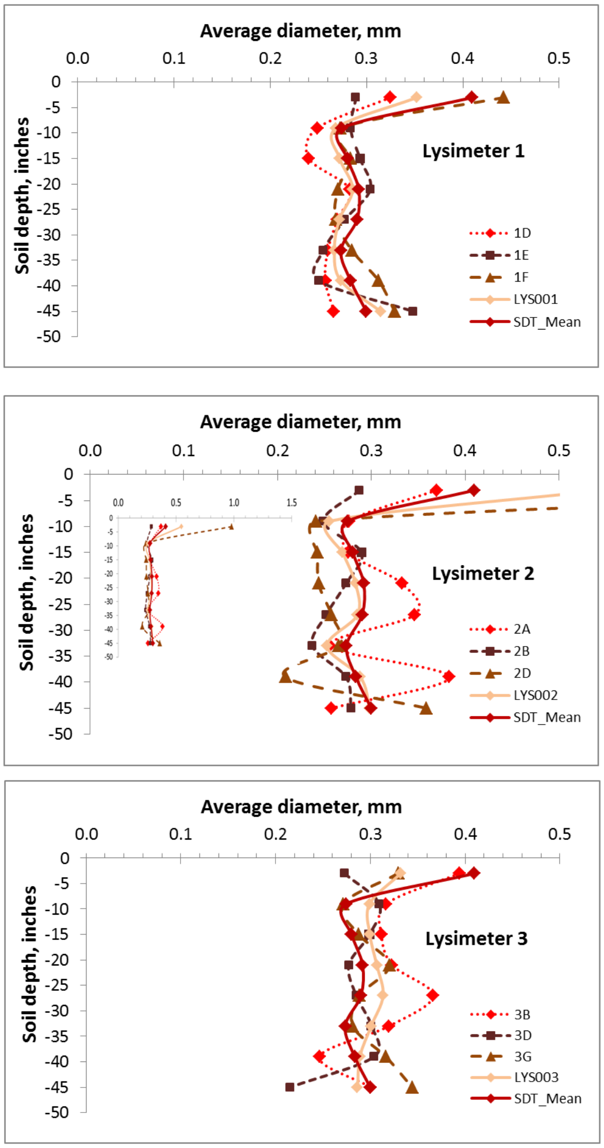


Figure 10. Mean of average diameter (AD) across all depths at different sites. Significant differences at p<0.05 level are indicated by different letters. ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site

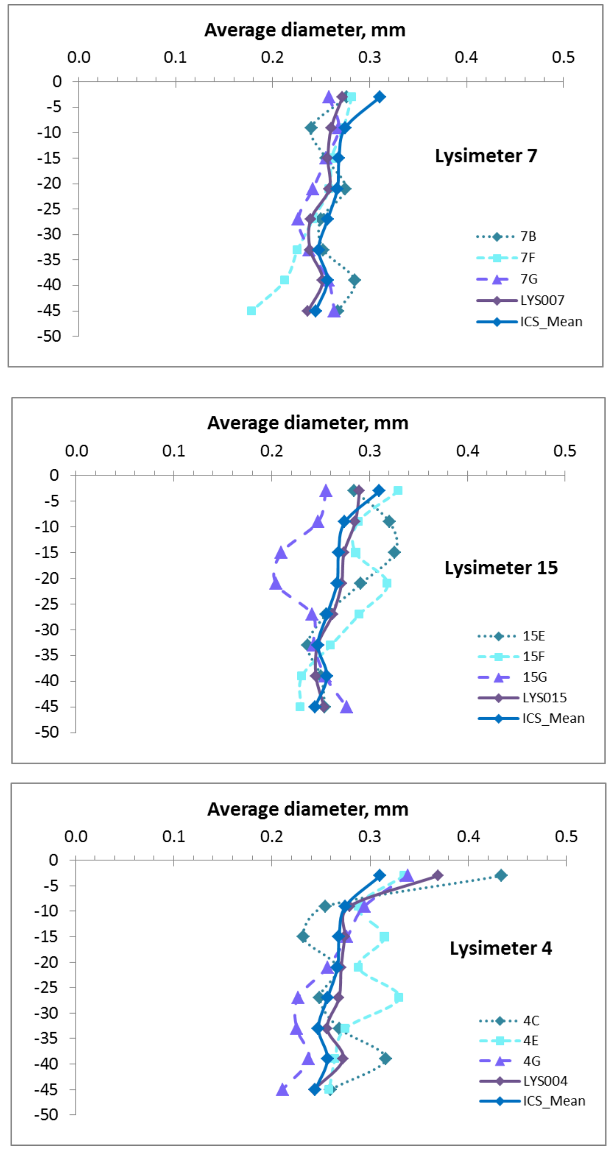
AD within sites for each soil core
The graphs in Figure 11 facilitate comparison of AD for each soil core across depths within sites. The graphs represent three soil cores from each lysimeter at ICS and SDT sites, and three soil cores from NS. ICS and SDT sites had two means: one for the lysimeter (mean of three cores) and one for the site (ICS or SDT, mean of nine cores). NS has only one mean for the three cores collected.

ICS soil cores had a similar range of AD for all soil cores (Figure 11). SDT also had similar ranges of AD for all cores except core 2D. This soil core had exceptionally thick roots at the shallow depth. The rest of the depths of this soil core had a similar range of AD as the others. NS soil cores were similar to each other.

a) SDT Cover Lysimeter



b) Corresponding ICS Lysimeter



c) Native Site

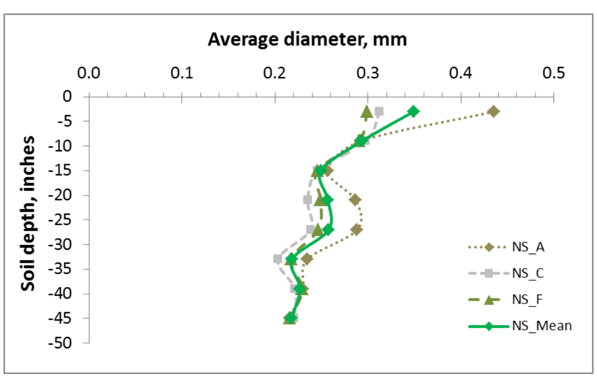


Figure 11. Comparison of average diameter (AD) for soil cores within sites: a) ICS-Integrated Cover System b) SDT-Shell Disposal Trenches. Inset graph shows all data points, including the outlier (AD =0.98 mm) core 2D c) NS-Native Site. Lysimeters 001 and 007 are on the north aspect at the toe of the slope. Lysimeters 002 and 015 are on the north aspect at the top of the slope. Lysimeters 003 and 004 are on the south aspect at the toe of the slope.

AD coefficient of variation and absolute value of the residuals
Coefficient of variation and absolute value of the residuals were analyzed to investigate the variation and heterogeneity of the AD. No differences in these metrics that would indicate greater heterogeneity of AD in one site than another were detected (Table 3).

Table 3. Summary of the analyses of the coefficient of variation and absolute value of the residuals for average diameter (AD) (num – numerator degrees of freedom; den – denominator degrees of freedom).

Response variable	Site	Mean ± SEM	Site		Site * depth	
			F (num, den)	p	F (num, den)	p
AD coefficient of variation, %	ICS	11.0 ± 2.1	0.82 (1, 4)	0.417	1.9 (2.1, 8.5)	0.207
	SDT	14.6 ± 4.0				
AD |residuals|, mm	ICS	0.01 ± 0.0	7.87 (1, 4)	0.049	2.75 (7, 28)	0.159
	SDT	0.02 ± 0.0				

Vegetation cover

Vegetation data showed no significant differences between ICS and SDT sites for grass cover ($p<0.91$), forb cover ($p<0.35$) and total cover ($p<0.11$). We could not statistically compare NS to the other sites due to lack of replication, but it is included in the graph (Figure 12).

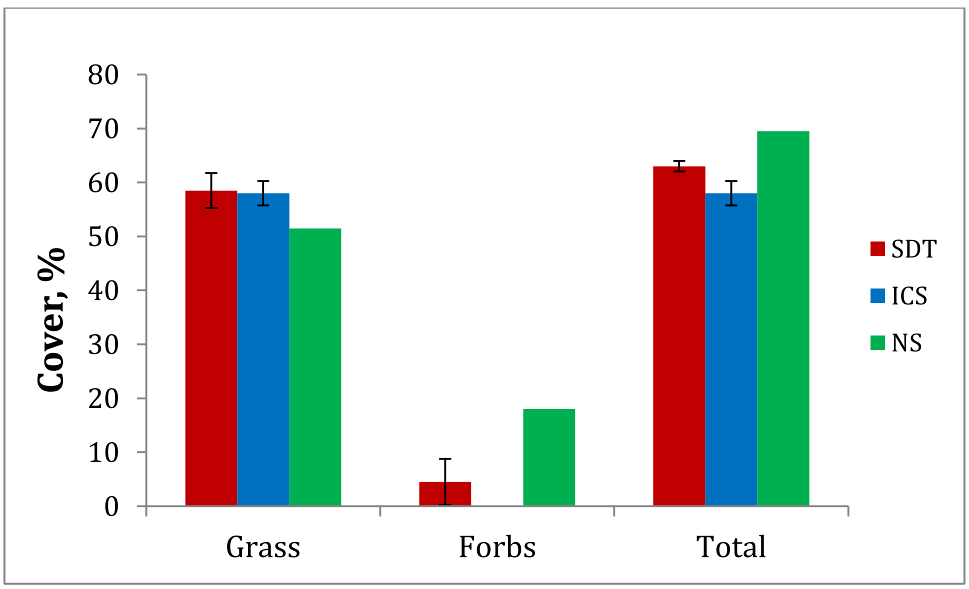


Figure 12. Vegetation cover (%) data comparison at RMA sites. ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site. Note NS does not have error bars due to lack of replication.

Discussion

Plants may play a role in greater percolation found in the SDT cover compared to the ICS cover, but we found little evidence for this. The most pronounced differences in rooting patterns between SDT and ICS covers were (1) a lack of roots at the deepest depth and (2) a slight increase in roots just above this level in SDT cover compared to the ICS cover (Figure 4). These differences in root distribution can be explained by a 6 inch (+/-)compacted layer in the SDT cover, which was not present in the ICS cover (Navarro 2015a). The compacted layer prevented root penetration and led to an accumulation of roots above the compacted zone, not unlike what is observed in root-bound potted plants. The compacted layer was created during cover construction to allow movement of heavy equipment across the site without damaging the polypropylene geotextile below it (Personal Communication, Navarro Research and Engineering, Inc. personnel, April 27, 2016). In addition to the decreased amount of plant root in the compacted layer, the compaction attribute may be adding to the amount of percolation at the SDT through desiccation cracking. These features may produce preferential pathways for soil water percolation.

Other than this, we found no differences between the two soil covers in root characteristics related to water extraction from the soil by vegetation (root length density and root mass per volume of soil). We also did not find evidence for a difference between the two soil covers in root characteristics that could contribute to increased percolation through large root channels or increased macropore space, or both (average root diameter).

The characteristics of roots in the covers were more similar to each other than to the native site (Figure 4, 5 and 7). The covers had greater RLD at shallowest soil depth and greater total RLD than the native site. We found greater AD in the SDT cover than in the native site, but the ICS cover was not different from either. We detected no other differences between the soil covers and the native site.

Differences in the abundance of forbs and grasses do not seem to explain the differences in percolation between the two cover types (Figure 12). It is possible that particular species within these functional groups have characteristics that affect movement of water through soil and plants in ways that contribute to the differences in percolation between SDT and ICS covers. This is one possible avenue of future exploration. However, the physical features that influence movement of water through plants and soil may not be appreciably different among the herbaceous species that occur on the covers of RMA.

Literature cited

Arsenault J.-L., S. Pouleur, C. Messier & R. Guay. 1995. WinRHIZO, a root-measuring system with a unique overlap correction method. HortScience, Vol. 30, pp. 906

RMA ICS Lysimeter Cover Soil SAP. Revision A. (Navarro, August 21, 2015)

RMA ICS Investigation and CMP Schedule. Revision B. (Navarro, September 17, 2015)

Image Analysis for Plant Science. Available at: http://www.regentinstruments.com/assets/winrhizo_about.html. Assessed on 09/23/2015.

Navarro Research and Engineering, Inc. 2015a. Rocky Mountain Arsenal Integrated Cover System, Schedule for Investigation of Percolation Exceedance of the Shell Disposal Trenches RCRA-Equivalent Cover and Development of a Corrective Measures Plan of Action, Revision B, September 17, 2015. U.S. Department of the Army and Shell Oil Company.

Navarro Research and Engineering, Inc. 2015b. Rocky Mountain Arsenal Integrated Cover System, Lysimeter Cover Soil Sample and Analysis Work Plan, Revision A, 21 August 2015. U.S. Department of the Army and Shell Oil Company.

WinRHIZO 2016. Basic, Reg, Pro & Arabidopsis for Root Measurement. User Manual. Regent Instruments Canada INC. pp.

Appendix

Table A1. Root length density (root length per volume): ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site.

Variable	Root length density, m/m³								
Depth, Inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Total
Control	13734	10724	11673	12022	9139	8256	6294	6901	78742
ICS_Mean	99251	26831	22456	21371	14732	11787	8338	8829	213595
LYS004	87046	28749	16617	12054	8750	5397	3976	5287	167876
4C	66872	41717	13839	13280	8934	3374	6184	7727	161929
4E	104493	15333	19723	13121	5628	4670	1687	1416	166071
4G	89772	29198	16290	9762	11686	8146	4057	6718	175630
LYS007	105564	27325	29644	29501	21812	16303	10718	11156	252023
7B	133357	27812	34043	25198	33653	29142	14480	12947	310632
7F	115573	32043	38145	49608	18827	6033	1804	3678	265710
7G	67761	22121	16744	13697	12955	13734	15870	16844	179726
LYS0015	105142	24420	21106	22558	13635	13662	10319	10043	220885
15E	132860	35420	15818	13765	12162	13290	7816	5353	236484
15F	136481	32942	43393	46077	15938	10149	6548	8248	299775
15G	46087	4898	4107	7832	12804	17545	16594	16528	126395
NS_Mean	38001	16506	16151	13290	10621	6462	4277	4236	109543
NS_A	49811	15253	17946	12992	4019	2480	1630	2341	106471
NS_C	23691	17568	18184	12408	14003	5017	6645	4517	102032
NS_F	40503	16696	12324	14469	13840	11888	4555	5849	120125
SDT_Mean	86814	34062	21070	19999	17860	13709	13153	2124	208790
LYS001	74327	32505	19054	16869	15381	12627	11302	1868	183933
1D	125325	43406	18670	21333	15275	12742	15754	2401	254906
1E	32621	21549	18667	14276	13218	7091	7696	768	115887
1F	65035	32559	19825	14997	17652	18048	10455	2434	181006
LYS002	120755	46953	19252	19592	14901	17666	11819	3072	254010
2A	89844	35284	14029	21953	14675	35290	14420	890	226385
2B	71182	44833	21968	16970	15952	12582	18722	7173	209382
2D	201240	60741	21758	19854	14077	5126	2316	1151	326262
LYS003	65361	22728	24904	23535	23297	10834	16338	1432	188429
3B	72192	16145	25158	21644	14981	1248	4694	1499	157561
3D	58646	26145	19202	20761	29897	14577	18686	2177	190091
3G	65246	25894	30353	28199	25012	16678	25633	620	217635

Table A2. Root length density coefficient of variation (RLD_CV): ICS-Integrated Cover System; SDT-Shell Disposal Trenches.

Variable	Coefficient of variation, %								
Depth, inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Total
ICS_Mean	34.20	44.52	50.56	56.63	32.80	48.36	60.64	60.83	23.43
LYS004	21.78	45.91	17.79	16.48	34.67	45.72	56.58	64.12	4.19
LYS007	32.14	18.22	38.32	62.16	48.91	72.18	72.31	60.62	26.39
LYS015	48.67	69.42	95.56	91.24	14.82	27.17	53.01	57.75	39.72
SDT_Mean	43.96	28.70	16.47	17.69	17.83	69.86	57.83	73.74	26.21
LYS001	63.29	33.62	3.50	23.02	14.42	43.39	36.23	50.99	37.82
LYS002	58.24	27.39	23.50	12.77	6.43	88.94	71.97	115.73	24.86
LYS003	10.36	25.09	22.41	17.27	32.64	77.24	65.28	54.52	15.96

Table A3. Root length density residuals (RLD_Res): ICS-Integrated Cover System; SDT-Shell Disposal Trenches.

Variable	Absolute value of RLD residuals, m/m³								
Depth, inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Total
ICS_Mean	8137	1608	4792	6211	4720	4260	2908	2361	30479
LYS004	12205	1918	5838	9317	5982	6390	4362	3542	45718
LYS007	6313	494	7188	8130	7080	4516	2380	2327	38428
LYS015	5892	2412	1350	1187	1097	1875	1981	1214	7290
SDT_Mean	22627	8594	2556	2358	3625	2638	2123	632	30146
LYS001	12487	1557	2016	3130	2478	1082	1851	256	24858
LYS002	33941	12891	1818	406	2958	3957	1334	948	45219
LYS003	21453	11334	3834	3536	5437	2875	3185	692	20361

Table A4. Mass per volume (MPV): ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site.

Variable	Mass per volume, gr/m³								
Depth, Inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Total
Control	613.0	135.5	211.3	165.6	172.9	178.0	143.4	91.6	1711.3
ICS_Mean	2223.6	399.4	360.5	336.0	187.0	141.1	102.5	94.7	3844.9
LYS004	2797.6	410.3	272.2	157.7	100.8	64.8	39.8	36.7	3879.9
4C	3706.6	439.3	140.2	133.5	87.8	52.1	70.5	60.5	4690.4
4E	2654.9	321.8	440.2	244.2	149.4	89.7	23.9	9.9	3933.9
4G	2031.4	469.7	236.1	95.5	65.0	52.8	25.2	39.7	3015.4
LYS007	1555.9	384.7	436.3	465.4	280.8	208.3	166.9	147.8	3646.0
7B	2217.1	387.0	496.8	451.3	459.0	375.9	247.9	167.1	4802.3
7F	1636.3	416.4	527.3	753.8	227.1	73.3	9.8	15.8	3659.6
7G	814.3	350.8	285.0	191.0	156.2	175.8	242.9	260.5	2476.3
LYS0015	2317.2	403.2	373.0	385.1	179.6	150.2	100.8	99.7	4008.8
15E	2128.2	618.6	318.2	222.7	142.5	165.6	88.3	29.3	3713.5
15F	4000.8	541.2	765.8	885.3	288.9	130.5	67.5	94.4	6774.2
15G	822.7	49.8	35.0	47.2	107.3	154.5	146.6	175.6	1538.7
NS_Mean	1711.2	262.9	182.2	135.3	107.1	40.8	33.9	37.7	2511.1
NS_A	4093.2	273.3	236.5	189.1	46.2	15.4	17.7	12.4	4883.8
NS_C	405.3	291.5	190.6	81.0	140.0	16.9	45.9	45.7	1216.9
NS_F	635.0	223.9	119.5	135.7	135.2	90.0	38.2	55.1	1432.5
SDT_Mean	2955.8	552.4	363.2	381.0	308.6	207.8	209.3	38.9	5016.9
LYS001	2013.3	513.9	323.9	315.4	256.9	205.6	140.7	33.6	3803.2
1D	2971.8	756.8	249.4	382.9	289.1	209.0	177.3	21.9	5058.2
1E	516.2	269.0	282.5	263.9	182.5	86.8	74.1	23.6	1698.6
1F	2551.9	516.0	439.8	299.4	299.1	320.9	170.7	55.2	4653.0
LYS002	4507.5	666.5	291.9	320.7	211.9	219.4	170.6	71.9	6460.4
2A	3089.3	597.7	214.8	505.5	301.5	485.0	236.7	22.6	5453.0
2B	1635.7	644.7	359.4	224.8	167.9	117.1	246.8	96.4	3492.8
2D	8797.6	757.1	301.5	231.8	166.4	56.2	28.2	96.7	10435.4
LYS003	2346.5	476.8	473.7	506.8	457.0	198.5	316.6	11.2	4787.1
3B	3358.1	371.1	513.9	448.5	373.1	24.8	41.7	14.3	5145.5
3D	1608.8	590.8	303.6	375.4	446.6	222.9	364.1	17.7	3929.9
3G	2072.6	468.6	603.6	696.6	551.3	347.7	544.0	1.5	5285.9

Table A5. Mass per volume coefficient of variation (MPV_CV): ICS-Integrated Cover System; SDT-Shell Disposal Trenches.

Variable	**Mass per volume coefficient of variation, %**								
Depth, inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Total
ICS_Mean	48.17	34.70	61.78	74.77	51.13	39.66	62.94	75.48	39.71
LYS004	30.26	19.04	56.29	48.98	43.34	33.14	66.61	69.41	21.62
LYS007	45.30	8.54	30.25	60.52	56.41	73.88	81.54	83.57	31.90
LYS015	68.94	76.51	98.79	114.79	53.63	11.96	40.68	73.45	65.61
SDT_Mean	62.62	27.61	29.61	34.17	27.12	81.57	64.60	63.94	39.73
LYS001	65.24	47.46	31.41	19.37	25.15	56.94	41.07	55.95	48.22
LYS002	83.99	12.29	24.92	49.91	36.62	105.72	72.35	59.43	55.40
LYS003	38.62	23.09	32.51	33.22	19.59	82.04	80.38	76.45	15.58

Table A6. Mass per volume residuals (MPV_Res): ICS-Integrated Cover System; SDT-Shell Disposal Trenches.

Variable	**Absolute value of MPV residuals, gr/m3**								
Depth, inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Total
ICS_Mean	445.1	9.8	58.9	118.9	62.5	50.8	42.9	38.7	132.6
LYS004	574.0	10.9	88.3	178.3	86.3	76.3	62.7	58.1	35.0
LYS007	667.7	14.7	75.8	129.3	93.7	67.2	64.3	53.1	198.9
LYS015	93.7	3.8	12.5	49.0	7.5	9.1	1.7	5.0	163.9
SDT_Mean	1034.5	76.1	73.7	83.9	98.9	7.7	71.6	22.0	962.3
LYS001	942.5	38.5	39.2	65.6	51.7	2.3	68.6	5.3	1213.7
LYS002	1551.8	114.1	71.3	60.3	96.7	11.6	38.7	33.0	1443.5
LYS003	609.3	75.6	110.5	125.9	148.4	9.3	107.3	27.7	229.8

Table A7. Average diameter (AD): ICS-Integrated Cover System; SDT-Shell Disposal Trenches; NS-Native Site.

Variable	Average diameter, mm								
Depth, Inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Mean
Control	0.50	0.31	0.32	0.33	0.37	0.40	0.35	0.35	0.37
ICS_Mean	0.31	0.27	0.27	0.27	0.26	0.25	0.26	0.24	0.27
LYS004	0.37	0.28	0.27	0.27	0.27	0.26	0.27	0.24	0.28
4C	0.43	0.25	0.23	0.27	0.25	0.27	0.32	0.26	0.28
4E	0.33	0.29	0.31	0.29	0.33	0.27	0.26	0.26	0.29
4G	0.34	0.29	0.28	0.26	0.23	0.23	0.24	0.21	0.26
LYS007	0.27	0.26	0.26	0.26	0.24	0.24	0.25	0.24	0.25
7B	0.28	0.24	0.25	0.27	0.25	0.25	0.28	0.27	0.26
7F	0.28	0.27	0.26	0.26	0.24	0.23	0.21	0.18	0.24
7G	0.26	0.27	0.26	0.24	0.23	0.24	0.26	0.26	0.25
LYS0015	0.29	0.29	0.27	0.27	0.26	0.25	0.25	0.25	0.27
15E	0.28	0.32	0.33	0.29	0.26	0.24	0.25	0.25	0.28
15F	0.33	0.29	0.29	0.32	0.29	0.26	0.23	0.23	0.28
15G	0.26	0.25	0.21	0.20	0.24	0.24	0.25	0.28	0.24
NS_Mean	0.35	0.29	0.25	0.26	0.26	0.22	0.23	0.22	0.26
NS_A	0.44	0.29	0.26	0.29	0.29	0.23	0.23	0.22	0.28
NS_C	0.31	0.30	0.25	0.24	0.24	0.20	0.22	0.22	0.25
NS_F	0.30	0.29	0.25	0.25	0.25	0.22	0.23	0.22	0.25
SDT_Mean	0.41	0.27	0.28	0.29	0.29	0.27	0.28	0.30	0.30
LYS001	0.35	0.27	0.27	0.29	0.27	0.27	0.27	0.31	0.29
1D	0.32	0.25	0.24	0.28	0.27	0.26	0.26	0.27	0.27
1E	0.29	0.28	0.29	0.30	0.28	0.26	0.25	0.35	0.29
1F	0.44	0.27	0.28	0.27	0.27	0.28	0.31	0.33	0.31
LYS002	0.55	0.26	0.27	0.28	0.29	0.25	0.29	0.30	0.31
2A	0.37	0.28	0.28	0.33	0.35	0.26	0.38	0.26	0.31
2B	0.29	0.25	0.29	0.27	0.25	0.24	0.27	0.28	0.27
2D	0.98	0.24	0.24	0.24	0.26	0.27	0.21	0.36	0.35
LYS003	0.33	0.30	0.30	0.31	0.31	0.30	0.29	0.29	0.30
3B	0.39	0.32	0.31	0.32	0.37	0.32	0.25	0.30	0.32
3D	0.27	0.31	0.30	0.28	0.29	0.30	0.30	0.22	0.28
3G	0.33	0.27	0.29	0.32	0.29	0.28	0.32	0.34	0.30

Table A8. Average diameter coefficient of variation (AD_CV): ICS-Integrated Cover System; SDT-Shell Disposal Trenches.

Variable	Average diameter coefficient of variation, %								
Depth, inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Mean
ICS_Mean	0.11	0.09	0.13	0.11	0.12	0.07	0.11	0.14	0.11
LYS004	0.15	0.08	0.15	0.06	0.20	0.11	0.15	0.11	0.13
LYS007	0.05	0.07	0.01	0.06	0.05	0.06	0.14	0.21	0.08
LYS015	0.13	0.13	0.22	0.22	0.09	0.05	0.05	0.09	0.12
SDT_Mean	0.37	0.07	0.08	0.10	0.12	0.06	0.19	0.18	0.15
LYS001	0.23	0.07	0.10	0.06	0.02	0.06	0.12	0.14	0.10
LYS002	0.69	0.07	0.09	0.16	0.19	0.06	0.31	0.18	0.22
LYS003	0.18	0.08	0.04	0.08	0.15	0.06	0.13	0.23	0.12

Table A9. Average diameter residuals (AD_Res): ICS-Integrated Cover System; SDT-Shell Disposal Trenches.

Variable	Absolute value of average diameter residuals, mm								
Depth, inches	0-6	7-12	13-18	19-24	25-30	31-36	37-42	43-48	Mean
ICS_Mean	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.009
LYS004	0.06	0.00	0.01	0.00	0.01	0.01	0.02	0.00	0.013
LYS007	0.04	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.014
LYS015	0.02	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.001
SDT_Mean	0.09	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.008
LYS001	0.06	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.012
LYS002	0.14	0.02	0.01	0.01	0.00	0.02	0.00	0.00	0.009
LYS003	0.08	0.02	0.02	0.02	0.02	0.03	0.01	0.01	0.003