Center for Environmentally Sustainable Transportation in Cold Climates

Evaluation of Effectiveness and Cost-Benefits of Woolen Roadside Reclamation Products

Rob Ament and Eli Cuelho, Western Transportation Institute, Montana State University,
Monica Pokorny and Stuart Jennings, KC Harvey Environment

December 2017

Prepared for:

Center for Environmentally Sustainable Transportation in Cold Climates
University of Alaska Fairbanks
P.O. Box 755900
Fairbanks, AK 99775

U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

INE/CESTiCC 101502

Evaluation of Effectiveness and Cost-Benefits of Woolen Roadside Reclamation Products

Prepared by:

Rob Ament, Road Ecology Program Manager
Eli Cuelho, Research Engineer
Western Transportation Institute
College of Engineering
Montana State University, Bozeman

Monica Pokorny, Senior Ecologist (former)
Stuart Jennings, Principal Scientist
KC Harvey Environmental, LLC
Bozeman, Montana

Prepared for:

Montana Department of Transportation
2701 Prospect Avenue
P.O. Box 201001
Helena, MT 59620-1001

December 2017

REPORT DOCUMENTATION PAGE			Form approved OMB No.
Public reporting for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestion for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-1833), Washington, DC 20503			
1. AGENCY USE ONLY (LEAVE BLANK)	2. REPORT DATE 12/2017	3. REPORT TYPE AND DATES COVERED Final Report: 03/2014 – 12/2017	
4. TITLE AND SUBTITLE Evaluation of Effectiveness and Cost-Benefits of Woolen Roadside Reclamation Products			5. FUNDING NUMBERS
6. AUTHOR(S) Rob Ament, Monica Pokorny, Stuart Jennings, Eli Cuelho Western Transportation Institute Montana State University – Bozeman POB 174250 Bozeman, MT 59717-4250			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Center for Environmentally Sustainable Transportation in Cold Climates University of Alaska Fairbanks Duckering Building, Room 245 P.O. Box 755900 Fairbanks, AK 99775-5900			8. PERFORMING ORGANIZATION REPORT NUMBER 101502
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLENMENTARY NOTES			
12a. DISTRIBUTION / AVAILABILITY STATEMENT No restrictions			12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This research project developed three types of products for study: woolen erosion control blankets (ECBs), wool incorporated into wood fiber compost at a 40:1 ratio (compost to wool, by weight), and wool incorporated into silt fence. The project, supported by Montana Department of Transportation (MDT) and the Center for Environmentally Sustainable Transportation in Cold Climates, compared the wool products' performance to roadside reclamation products commonly used for revegetating cut slopes: straw/coconut (coir) ECB, wood fiber compost and woven plastic silt fence. Three versions of wool silt fence were developed by the project, yet, even more versions are needed to arrive at a commercially viable product. Wool silt fence was the least promising of the three types of reclamation materials. The primary measure for success for ECBs and wool additive to the compost was the amount of seeded or desired vegetation they established after two growing seasons. The research team evaluated the performance of the woolen and standard products by measuring the percentage of canopy cover of each plant species present in each treatment plot. Canopy cover measures the percentage of ground that is covered by a vertical projection of a plant's foliage. To conduct the comparative analysis, researchers calculated an average percent canopy cover for each functional group: seeded native grasses, desired non-seeded (volunteer) grasses and forbs, and weeds. There was no statistical difference in the mean canopy cover of seeded grass species of the compost treatment (control) compared to the cut wool with compost treatment, 6.4% and 10.2%, respectively. Thus, the project could not determine that cut wool pieces provided a benefit to plant establishment and growth when it is added to compost material. Further experimentation to determine the ideal ratio of wool pieces to add to compost is warranted. The two best performing treatments (i.e. greatest seeded grass establishment) were the rolled wool/straw ECBs. The 100% wool ECB and 50% wool/50% straw ECB had the greatest mean seeded grass canopy cover after two years. Both of these wool ECBs had more seeded grass canopy cover than the standard 70% straw/30% coir ECB demonstrating their potential as a commercially viable product for roadside revegetation applications. Laboratory tests of the wool/straw ECB demonstrated it was comparable to the specifications of a short-term (Type II B or C) standard ECB used along MDT roadways. Future product development of the wool/straw ECB should focus on improving the shear strength at high flows so it meets all required Type III specifications.

14- KEYWORDS : roadside, land reclamation, right-of-way, revegetation, erosion control, silt fence, compost, soil stabilization, soil conservation, costs benefits,			15. NUMBER OF PAGES 100 16. PRICE CODE N/A
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT N/A

DISCLAIMER

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document. The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

AUTHOR'S DISCLAIMER

Opinions and conclusions expressed or implied in the report are those of the author(s). They are not necessarily those of the funding agencies.

Acknowledgements

We appreciated the financial support of the Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC), which is an University Transportation Center based at the University of Alaska, Fairbanks. Our project's use of wool, a fiber appreciated for millennia in cold regions throughout the world, is perhaps a perfect fit for CESTiCC and its proponents of sustainable transportation.

The authors would like to thank the technical advisory committee for providing their expertise and sharing information for this project:

Kris Christensen

Jennifer Davis

Scott Helm

Phil Johnson

Alan Woodmansey

We are indebted to the Montana wool experts and producers who taught us about wool production, its manufacture into products and the wool industry, in general. Contributors were Sue James and Ed James of Sugar Loaf Wool Carding Mill, LLC, Becky Weed and Dave Tyler of Thirteen Mile Lamb and Wool Company, and Thayne Mackey of Brookside Woolen Mill. They helped us develop many different wool products for the project.

We thank Phil Johnson for his excellent idea to explore wool as a potential fiber for improving roadside reclamation materials. We appreciated the help from Michael Ramy Jr. and Brian Dingels of Ramy Turf Products and Ero-Guard, Inc., respectively. Their interest in participating in this research. Their knowledge and skills of ECB manufacturing was instrumental in the development of the rolled woolen ECB products and directly contributed to the success of this research.

We appreciated Mirjam Barrueto's skilled statistical analyses and help in the presentation of results.

Table of Contents

1 Introduction 1

2 Background 2

3 Materials Selection 4

3.1 Materials and Methods 4

3.2 Results 15

3.3 Preliminary Field Trials 17

3.4 Geotextile Manufacturing 19

3.5 Recommendations 21

4 Lab Tests 23

4.1 Lab Tests 23

4.2 Materials and Methods 24

4.3 Results 26

4.4 Conclusions 37

5 Field Tests 39

5.1 Materials and Methods 39

5.2 Results 48

5.3 Conclusions 60

6 Cost Benefit Analysis 63

6.1 Methods 63

6.2 Results 64

6.3 Conclusions 74

7 Conclusions 75

7.1 Laboratory Tests 75

7.2 Field Tests 76

7.3 Cost Benefit Analysis 77

8 Recommendations 79

9 References 81

10 Appendix A: Highway 287 Vegetation Monitoring 2017 83

List of Tables

Table 1: Woolen products identified or developed for roadside reclamation from abroad, existing U.S. products for horticulture or potential U.S. products to be developed or used in a new way. . 5

Table 2: Summary of wool products reviewed, and those selected for further testing in the project. 16

Table 3: Woolen products identified for preliminary field trials. 17

Table 4 : Typical MDT perennial grass seed mix and seeding rate used for preliminary test plots. 18

Table 5: Summary of wool materials developed for silt fence, rolled erosion control blanket or as an additive to wood compost and selected for field tests. 20

Table 6: Woolen silt fence and erosion control fabrics identified for lab and field tests. 22

Table 7: Rolled erosion control blankets manufactured for lab and field tests. 22

Table 8: The products and lab tests evaluated. 25

Table 9: Analytical methods for products and soil samples. 26

Table 10: Mass per unit area of the wool reclamation products[1]. 28

Table 11: New product naming convention based on the product's actual weight and proportions. 29

Table 12: Results of the tensile property tests for the wool/straw and straw/coconut erosion control blankets. 29

Table 13: MDT material specifications for temporary rolled erosion control, 2014. See MDT Materials Specifications Manual, Table 713-5. 30

Table 14: Specifications for temporary rolled erosion control materials. See MDT Material Specifications Manual Table 713-4, 2014 supplement. 30

Table 15: Results of the maximum C factor (ASTM D 6459) test for 40% Wool / 60% Straw ECB. 31

Table 16: Results of the minimum shear stress test (ASTM D 6460) for wool/straw ECB. 33

Table 17: Analytical test results for the product materials and study site soil. 35

Table 18: Wool silt fence field locations installed August 28, 2014. 41

Table 19: Treatments tested in experimental plots along U.S. Highway 287, Three Forks, MT. 43

Table 20: Randomized block design of eleven treatments replicated eleven times at U.S. Highway 287 field site. 44

Table 21: The six ECB treatments tested at the Transcend field site. 47

Table 22: Soil chemical characteristics before and after treatment, U.S. Highway 287 site. 51

Table 23: Mean percent canopy cover of plant groups by treatments at Highway 287 test site. . 52

Table 24: P-values generated from independent t-tests of mean seeded species canopy cover between ECB treatments. Significant values (< 0.05) highlighted for interpretation. See Table 24 for mean values. 54

Table 25: P-values generated from independent t-tests of mean weed species canopy cover between ECB treatments. Significant values (< 0.05) highlighted for interpretation. See Table 24 for mean values. 55

Table 26: Soil chemical characteristics before and after treatment, Transcend test slope, Lewistown, MT. 56

Table 27: Mean percent canopy cover of plant groups by treatments at Transcend test site in 2016. 57

Table 28: Mean percent canopy cover of plant groups by rolled erosion control treatment or control at Transcend test site in 2017. 57

Table 29: Sheep and lamb inventory (USDA, NASS 2014). 64

Table 30: Estimated costs of materials and processes for manufacturing erosion control materials.: 68

Table 31: Costs of various wool and standard non-wool ECB products, excludes production shipping costs. 68

Table 32: Summary of wool silt fence costs. 73

Appendix A Table 33. Treatments selected for vegetation cover and soil monitoring in 2017, U.S. Highway 287, Three Forks, MT. 84

Appendix Table 34. Average vegetative canopy cover by treatment type in monitoring years 2015, 2016, and 2017. 85

List of Figures

Figure 1: Biowool, BW 400, product sample from Cirtex Industries in New Zealand. 6

Figure 2: Wool bag made from woven Twool. 8

Figure 3: Woolch™ product has wool and wood fibers. 9

Figure 4: Wet felted wool samples from Sugar Loaf Wool Carding Mill. 10

Figure 5: Wool batting produced at Sugar Loaf Wool Carding Mill in Hall, Montana. 12

Figure 6: Washed, scoured and shredded wool sample from Brookside Woolen Mill. 13

Figure 7: Demonstration of two erosion control blankets using different ratios of wool and straw produced by Ero-Guard. 14

Figure 8: Close-up photograph of a 60 percent wool/40 percent straw erosion control blanket .. 14

Figure 9: Field trial set-up to identify the products for large-scale testing. 18

Figure 10: Seedlings are able to penetrate the 68 g/m^2 and 136 g/m^2 carded wool batting (left), but had difficulty penetrating the 203 g/m^2 and 271 g/m^2 carded wool batting (right). 19

Figure 11: Ero-Guard experimenting with a wool-straw combination for fill in a rolled erosion control blanket. 21

Figure 12: Images of intensities for C factor test (ASTM D 6459) for wool/straw erosion control blankets (photo courtesy of TRI). 32

Figure 13: Images of flow levels for minimum shear stress (ASTM D 6460) test for wool/straw ECB (photos courtesy of TRI). 34

Figure 14: Field test site locations in Montana. 40

Figure 15: Three generations of wool silt fence and standard woven plastic silt fence tested in field trials, 2014 – 2016. 42

Figure 16: Above: Experimental layout of 9 treatments with eleven replications at the Highway 287 field site, October 2014 (wool/straw ECB treatments installed in 2015 not pictured). Below: Vegetation that developed in the 11 treatments by July 2017. 45

Figure 17: Test slope (2H:1V) constructed at Transcend, a WTI-MSU experimental station in Lewistown, MT. 46

Figure 18: One replication of the six treatments at the Transcend test slope. 47

Figure 19: Photo monitoring the three generations of wool silt fence developed and tested in field trials along U.S. Highway 12, 2014 – 2016. 49

Figure 20: Overview of the Transcend test slope vegetative cover, June 2017. 58

Figure 21: Close-up of the 100% wool ECBs deployed on test slope at Transcend, June 2017. . 59

Figure 22: Replications of erosion control products along U.S. Highway 287, Three Forks, Montana, October 2014. Plot dimension is one meter square and all treatments are covered with mesh netting stapled in place. 67

Figure 23: June 2016 field monitoring found shrinkage of a pure wool needle punched batt along U.S. Highway 287 near Three Forks, MT. The product initially covered the entire one square meter within the PVC frame 67

Figure 24: Example of wool combined with straw as fill between two biodegradable net layers in a rolled erosion control blanket........ 69

Figure 25: Equipment that manufactures rolled ECBs, Ero-Guard, Mapleton, MN. 70

Figure 26: Close-up of a straw and jute net ECB manufacturing at Ero-Guard, Mapleton, MN. 70

Figure 27: (a) Rolled silt fence constructed of two burlap layers sewn together with cut wool pieces as filler. (b) Backlit burlap and wool silt fence shows the lack of consistency in the distribution of the wool pieces in the center layer of the fence. 73

Appendix Figure 28. Desirable vegetation cover from 2015-2017 for selected treatment plots. 86

Appendix Figure 29. Undesirable vegetation cover from 2015-2017 for selected treatment plots. 86

Glossary

Batt	a piece of felted or carded wool material in rolls or sheets
Carding	a mechanical process to disentangle unorganized clumps of wool fiber and align them to be parallel with one another
Felt	a textile that is produced by matting, condensing and pressing fibers, such as wool, together
Greasy wool	raw, uncleaned wool that contains lanolin
Needle felted	“barbed” needles in machines enter wool and grab top layers and intertwine them with interior layers of fibers in a continuous repeated process to make wool fabric
Noil	short fiber removed by the combing of wool
Roving	a slightly twisted roll or strand of unspun wool fiber
Scour	the removal of wool wax (lanolin), suint (perspiration), dirt, excrement, dust and other matter from the fleece in water.
Wet felted	warm soapy water is applied to layers of wool and it is repeatedly agitated and compressed to make a single piece of fabric
Worsted	wool or yarns that have a long staple length (4-inch fibers and longer only), are carded *and* combed, are stronger, finer, smoother and harder than woolen yarns/wool

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

1 INTRODUCTION

This document evaluates the effectiveness of woolen roadside reclamation products. The overall objective of the project is to evaluate wool products that can be used for roadside reclamation projects by the Montana Department of Transportation (MDT) and other transportation agencies. The project seeks to develop and test potential wool products that can be easily produced as complementary or replacement products to existing standard best management practices (BMPs). There were four objectives which are discussed further in Chapters Three through Six. The specific objectives were to:

1. Review existing woolen reclamation materials and products and develop new wool reclamation products for roadside purposes (See Chapter Three).

2. Use geotextile and analytical laboratory tests to compare standard reclamation products to their woolen equivalents. The results will assure transportation agencies that woolen materials tested in this project are similar or comparable to existing reclamation products (See Chapter Four).

3. Field test woolen reclamation products and standard erosion control blankets (ECBs) and compost products to determine if the woolen products provide equal or improved seeded species establishment and erosion control compared to the traditional commercial products being used by MDT (See Chapter Five).

4. Conduct a cost-benefit analysis to evaluate the cost of producing woolen versus standard reclamation products (See Chapter Six)

2 BACKGROUND

Highway right-of-way management following construction on MDT lands requires creating conditions conducive to the establishment, growth, and persistence of reclamation plantings while controlling soil erosion and surface runoff. Woolen reclamation BMP products have many attributes that may make them superior to existing standard materials. This project seeks to develop and test the effectiveness of wool-based products for erosion control, soil retention and vegetation establishment. Wool products will be compared to existing reclamation products, ones that often use imported coconut fiber (coir) in erosion control fabrics or are made of synthetic non-biodegradable geotextile materials.

Erosion control fabrics generally meet the requirements established by the Erosion Control Technology Council and the U.S. Department of Transportation, Federal Highway Administration's standard specifications for construction of roads and bridges on federal highway projects [FP-03 2003 Section 713.17, Type 3.B]. There are several types of erosion control blankets (ECBs): temporary, extended, and semi-permanent. One of the most commonly used erosion control blanket produced is comprised of two layers of sisal netting filled with straw and coconut fibers and loosely stitched together. According to several manufacturer's product specifications, ECBs have a functional longevity of up to eighteen months. These ECB products are intended to reduce soil erosion, water run-off and improve the environment for revegetation. Some ECBs also may provide soil moisture retention to aid in seedling establishment and plant growth.

Roadside reclamation products containing wool may perform similarly or better than traditional straw/coconut ECBs. Scoured weed-seed free wool can store up to 400% of its weight in water (Upton 2003). Wool becomes saturated at 33% of its weight of moisture-free fibers (D'Arcy 1990). That is, when scoured wool absorbs water greater than 33% of its weight, the moisture is available for plant growth. This characteristic could make woolen ECBs more advantageous in drier climates and in areas with sandy or porous soils. In addition, sheep wool contains 16% to 17% nitrogen (Simpson and Crawshaw 2002) and can act as a slow release fertilizer for plant growth (Herfort 2010). Research from European testing of the use of woolen fabrics for establishing vegetation on green roofs resulted in over three times more plant canopy cover when wool was used in mats compared to traditional coconut fibers mats (Herfort 2010). Waste wool pellets are also marketed as fertilizer in both the U.S. and Germany (Bohme et al. 2010). In addition to providing fertility, the wool pellets hold 20 times their weight in water (Wild Valley Farms 2016).

Two other potential woolen roadside reclamation materials explored for this project are silt fence which replaces the existing standard woven plastic silk fence with a fully biodegradable one, and using pieces of wool as an additive to wood-based mulch. The standard silt fence normally deployed by transportation agencies is currently made of synthetic woven materials and must be removed after a highway project is concluded. There is potential for the development of a wool silt fence that could be 100 percent biodegradable and potentially be left in place, leaving sediments and the reclamation site undisturbed at the conclusion of a roadside reclamation project.

With wool's high nitrogen value and water holding capacity it may be a relatively inexpensive addition to wood mulch (compost) to boost revegetation establishment. Wood mulch is commonly used after seeding roadsides to protect and enhance seedling growth. In other countries, New Zealand for example, pelletized sheep wool (often mixed with sheep manure) is commercially available and can be added to compost to speed up the decomposition process or is sold as a fertilizer. In Poland, waste wool was added to horticultural crops, resulting in higher yields (Gorecki and Gorecki 2010). Adding wool to standard wood compost on roadsides may serve to increase nitrogen availability for seedling establishment and growth and improve moisture retention of the compost blanket. Moister mulch may potentially increase its rate of decomposition thus make a variety of nutrients other than nitrogen (N) available for plant establishment and growth.

3 MATERIALS SELECTION

This project sought to identify and develop wool products with the potential for roadside applications. A review of existing woolen reclamation materials and woolen products with the potential to be further developed for roadside reclamation purposes was conducted. There were three product arenas that were explored:

- Existing woolen products produced abroad (i.e. New Zealand) that are not available in the United States.
- Woolen products made in the U.S. for horticultural or residential purposes that could possibly be utilized in roadside reclamation efforts.
- New woolen reclamation materials that could be produced by Montana wool producers or other manufacturers.

The most promising woolen materials for roadside reclamation were reviewed, explored, developed, and secured. The research team also sought to assure that there was an adequate supply of the wool reclamation product to meet the needs of the transportation sector, assuming the product would prove to be successful after its acquisition and/or development, and its performance in lab, field, and cost-benefit evaluations.

3.1 Materials and Methods

Woolen products were identified for testing in roadside applications by searching for products on the internet, working with the Montana Wool Lab at Montana State University, and contacting and working with U.S. based wool producers and woolen mills. Woolen products were identified and placed into three broad categories: 1) wool products produced abroad, 2) wool products currently used for horticulture and landscaping in the U.S. that may be suitable for roadside applications, and, 3) U.S. wool mill products with the potential to be developed further for roadside reclamation uses and/or products (Table 1).

Table 1: Woolen products identified or developed for roadside reclamation from abroad, existing U.S. products for horticulture or potential U.S. products to be developed or used in a new way.

Product and Manufacturer	Produced Abroad	Existing U.S. Product	New Use or Product Development
BioWool 400, wool matting, Cirtex Industries, New Zealand	X		
Biomac Woolmulch, Maccaferri, New Zealand	X		
TerraMat Wool, GeoTech Systems Ltd, New Zealand	X		
EcoWool Mulch Mats, Advance Landscape Systems, New Zealand	X		
Wool Mulch Mat, Terra Lana, New Zealand	X		
Twool®, Twool Twine, England	X		
Thermafleece, Eden Renewable Innovations, England	X		
Woolch™, Grazeland Farm, Minnesota, U.S.		X	
Blow-in Wool Insulation, Brookside Woolen Mill, MT		X	
Wet Felted Wool Batts, Sugar Loaf Wool Mill, MT			X
Needle Felted Wool Batts, Brookside Woolen Mill, MT			X
Carded Wool Batting, Sugar Loaf Wool Mill and Thirteen Mile Lamb and Wool Company, MT			X
Noils, Montana Wool Lab, MT			X
Loom Salvage, Faribault Woolen Mill, MN			X
Washed/Scoured Wool, Brookside Woolen Mill, MT			X
Wool / Straw ECB, Ero-Guard, MN			X

3.1.1 Existing Woolen Products Produced Abroad

The top four wool producing countries in the world are China, Australia, New Zealand, and the United Kingdom (United Nations 2012). A literature and internet search located woolen products produced abroad that are not available in the United States. For products with potential for use along roadsides, product samples were procured to review product integrity and qualities prior to purchasing. Promising foreign product samples were sent to Montana woolen producers to determine whether they could make a similar product from waste wool.

3.1.1.1 BioWool, Cirtex Industries

Cirtex Industries in New Zealand manufactures BioWool, a non-woven, 100% pure wool matting using recycled and fleece wool. Cirtex BioWool 400, shown in Figure 1, is a biodegradable wool matting used for protecting cut faces of slopes and exposed soil from wind and water erosion, and is used around horticultural plantings where it provides plants with nutrients as it degrades (Cirtex 2014). In addition, BioWool assists vegetation establishment while insulating the seed and root zones from extremes of heat and cold through moisture penetration. The BioWool 400 fabric also suppresses weeds while allowing establishment of plants, therefore reducing the need for chemical sprays (Cirtex 2014). Being a natural, recycled product also provides aesthetic advantages over synthetic products. BioWool 400 is available in 2 meter (m) by 50 m (6.6 feet (ft) x 164 ft) rolls.

Figure 1: Biowool, BW 400, product sample from Cirtex Industries in New Zealand.

3.1.1.2 Woolmulch, Geofabrics New Zealand, Ltd.

Geofabrics New Zealand, Ltd. is a geosynthetics company specializing in providing products and engineering solutions for the preservation of the environment. Geofabrics® manufactures Biomac Woolmulch, 100% wool matt reinforced with a jute mesh. It is used for landscaping and plant establishment, along with protecting soils from erosion. Biomac Woolmulch has the following advantages over synthetic products (Geofabrics 2015):

- Wool provides insulation for improved plant growth
- The non-woven structure allows surface water penetration while reducing evaporation of moisture from the soil
- Better surface contact is achieved which improves erosion resistance to overland flow
- Its biodegradable material releases valuable nutrients for improved plant growth
- Thicker wool mats reduce sunlight for inhibiting weeds

Biomac wool matting is supplied in two densities: 500 grams (g)/m^2 and 300 g/m^2 (14.8 ounces (oz)/yard (yd)^2 and 8.9 oz/yd^2).

3.1.1.3 TerraMatt Wool System, Geotech Systems, Ltd.

Geotech Systems, Ltd. of New Zealand makes three different wool products for erosion control and to help vegetation establishment via its TerraMatt Wool system. The three wool products are: plain wool blanket, the wool blanket reinforced with jute, and wool plant collars. These short-term erosion control and revegetation blankets remain functional for 12 to 24 months. All three products are needle punched wool mats made from recycled sheep's wool fiber.

TerraMat Wool is designed to be an effective soil erosion protection system that also promotes the establishment of vegetation on roadside slopes up to 1:1 slopes and can be applied to steeper slopes with additional staking (Geotech 2013). Thus, TerraMat products can be used for embankments, filled side slopes, drainage channels, and stream banks, along with an applicability for roadsides.

3.1.1.4 EcoWool Mulch Mats, Advanced Landscape Systems

EcoWool Mulch Mats made by Advance Landscape Systems in New Zealand are 100% natural and manufactured from waste wool. EcoWool Mats are 500 g/m^2 (14.8 oz/yd^2) and sold in two sizes: 450 x 450 mm (17.7 inch (in) x 17.7 in) or 360 millimeter (mm) x 360 mm (14.2 in x 14.2 in) squares. Due to their pre-cut nature and easy placement around tree/shrub bases, EcoWool Mulch Mats are recommended in any size tree and shrub planting projects where soil conservation and weed suppression are required (Advance Landscape Systems 2011).

The EcoWool Mulch Mat allows for effective penetration of water and fertilizer, as it stays damp for hours after wetting while reducing evaporation and erosion. Because the product is made from wool, it contains nitrogen, sulfur, sodium, potassium, and magnesium that are released into the soil as it gradually degrades two to three years after installation (Advance Landscape Systems 2011). Eco-Wool also suppresses unwanted vegetation growth around establishing plants by blocking out sunlight (Advance Landscape Systems 2011).

3.1.1.5 Wool Mulchmat, Terra Lana

Terra Lana's Mulchmat produced in New Zealand is a fully biodegradable non-woven wool matting made from pure and recycled wool. Since it is a natural product made from wool, Mulchmat is biodegradable and releases nutrients giving growing plants a boost (Terra Lana 2014). Mulchmat suppresses weeds, prevents soil erosion and soil moisture loss, while insulating plants from temperate extremes. The benefits of Mulchmat aid in the establishment of plant species when used in landscape plantings, horticulture, and native species re-revegetation. Terra Lana Mulchmat has a density of 500 g/m^2 (14.8 oz/yd^2).

Terra Lana also produces a reinforced version of the Mulchmat that is strengthened with jute fiber (Terra Lane 2014). This product is ideal for stabilizing soil on slopes and is also 500 g/m^2 (14.8 oz/yd^2) consisting of 300 g/m^2 wool (8.9 oz/yd^2) and 200 g/m^2 jute (5.9 oz/yd^2). Both products are supplied in rolls or pre-cut mats for placing around trees (Terra Lane 2014).

3.1.1.6 Twool® Twine, Provenance Company, Ltd.

Twool® twine is a 100% wool, British alternative to imported jute twine. It is made from 'lustre' long wool from a rare breed of Whiteface Dartmoor sheep (Twool® 2012). The long staple length makes the Twool® exceptionally strong and durable while maintaining wools soft and springy attributes. Twool® is available in 100 m (328 ft) and 35 m (115 ft) spools, and in woven bags

(Figure 2). Twool® is currently used as a garden product that is compostable, turning into a slow-release fertilizer as it degrades (Twool® 2012).

Figure 2: Wool bag made from woven Twool.

3.1.1.7 Thermafleece, Edan Renewable Innovations

Thermafleece Original is an insulation product that combines natural and recycled fibers for an optimal density for thermal and acoustic performance. The product is 85% wool, 15% polyester binder for enhanced performance, durability and sustainability. Eden Renewable Innovations' research found that using 75% wool in combination with recycled fibers outperforms alternative products with a higher percentage of wool (Thermafleece 2014). The wool fiber is capable of absorbing more moisture (40% of its weight) than any other natural fiber due to its high fiber saturation point. The complex protein structure of wool fibers allows it to absorb indoor air pollutants creating a healthier indoor environment (Thermafleece 2014). Thermafleece Original is sold in 1,200 meter (3,937 ft) sections. It is available in 400 mm or 600 mm (15.7 in or 23.6 in) widths and 50 mm, 75 mm and 100 mm (2 in, 3 in, and 4 in) thicknesses.

3.1.2 Two Existing U.S. Woolen Products

Literature and internet searches were used to identify horticultural or landscaping woolen products made in the U.S. that could possibly be utilized in roadside reclamation efforts. One product, Woolch is used in gardening but may have roadside applicability. Another product is blow-in wool insulation that may be ideal for incorporating in to roadside hydro-mulching or blow-on compost applications.

3.1.2.1 Woolch™, Grazeland Farm, Minnesota

Woolch™ is a blend of recycled wool and wood. The wool is waste fiber from the Faribault woolen mill in Minnesota and the wood slivers are a waste by-product from a sawmill. The wool and wood fibers are blended, sprayed with a green vegetable-based dye, and then fused together via a roller and heat process (Figure 3). Woolch™ provides effective weed control for two years. Woolch™ allows for water and nutrients to move through the fibers and plant stolons can root through it from the top.

The wool mulch stabilizes soil temperature, retains moisture, and increases plant yields. As it degrades, it provides nutrients to the soil. It is used by preparing the soil for planting, installing Woolch™ on the soil surface, and cutting holes in the fabric for planting. The Woolch™ product is available in row strips 38 x 152 cm (15 x 60 in), tomato pad squares 51 x 51 cm (20 x 20 in), container mats 1.2 x 1.5 m (4 x 5 ft), and large rolls 1.5 x 24.4 m (5 x 80 ft).

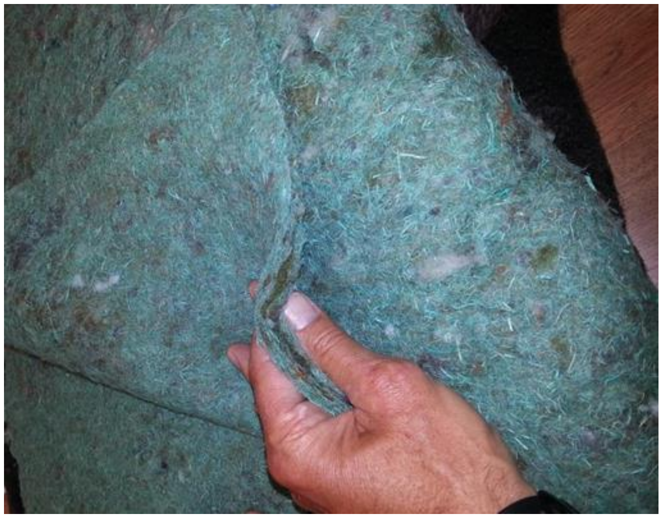


Figure 3: Woolch™ product has wool and wood fibers.

3.1.2.2 Blow-in Wool Insulation, Brookside Woolen Mill, Montana

Blow-in insulation is washed and scoured wool that is cut into 1.9 centimeter (cm) (¾ in) pieces (Montana Green Insulation 2011). The length and color of the wool fibers are not important. The cut wool fibers can easily pass through a blow-in insulation machine to residential attics. The loose pieces can be applied at various densities and is more useful for filling small, uneven spaces than standard bats. Brookside Woolen Mill markets this on the internet under the name Montana Green Insulation.

3.1.3 New Woolen Reclamation Materials

The last category of woolen products that were reviewed and evaluated for potential further experimentation were products that are readily made in the U.S. but are made for non-roadside reclamation purposes. These are products produced by Montana wool producers or other manufacturers where the roadside use could diversify the product's usefulness and versatility, and expand market and income possibilities for producers. For example, a strong felted wool material could be used to replace non-biodegradable silt fence. The wool silt fence equivalent would not have to be removed at the end of the construction project and could add nitrogen to the area as it decomposes.

To identify potential wool products currently being manufactured by woolen mills in Montana, the research team visited and met with Brookside Woolen Mill of Malta, Montana (Brookside); Thirteen Mile Lamb and Wool Company of Belgrade, Montana (13 Mile); and, Sugar Loaf Wool Carding Mill in Hall, Montana (Sugar Loaf). We also worked with the manager of the Montana Wool Lab (Dr. Lisa Surber) at Montana State University to identify potential wool products and producers for this research project. Finally, we engaged producers of industry standard erosion control blanket (ECB) products made of coconut and straw to discuss the potential for substituting imported coconut fibers with locally developed wool.

3.1.3.1 Wet Felted Wool Blanket, Sugar Loaf Wool Carding Mill, Montana

Felt is a textile that is produced by matting, condensing and pressing fibers together. The wool is first washed and scoured (cleaned and lanolin removed). Wool can be transformed into felt using techniques such as needle felting and wet felting. Wool is manipulated during wet felting when hot soapy water is applied to layers of animal hairs placed at ninety-degree angles to one another. Repeated agitation and compression causes the fibers to hook together into a single piece of fabric. Felting can be used to make simple shapes or flat pieces. Felted material is used in a variety of industries including automotive, musical instruments, home construction, home décor, and clothing. For example, in the automotive industry, felted wool damps the vibrations between interior panels and prevents dirt from entering joints.

Sugar Loaf produces wet felted wool mats. These mats are the same weight approximately 400 g/m^2 (12 oz/yd^2) as roadside reclamation materials produced in New Zealand (Figure 4). Sugar Loaf offers the options of producing the wet felted mats in a variety of weights in a three-foot width. Sugar Loaf wet felted wool has the potential for making the following roadside reclamation products: ECB, weed mat, or silt fence.

Figure 4: Wet felted wool samples from Sugar Loaf Wool Carding Mill.

3.1.3.2 Needle Felted Wool Blanket, Brookside Woolen Mill, Montana

Needle felting uses needles in machines to enter wool and grab top layers and intertwine them with interior layers of fibers in a continuous repeated process to make wool fabric. The wool is first washed and scoured. Needle felting can more easily control the final shape of the product. The entangled and compressed felt produces a strong material suitable for a variety of uses.

Brookside produces needle felted wool mats. This local Montana wool mill can produce the wool mats in a variety of weights, widths, and densities (made by manipulating the number and direction of needle passes). Brookside needle felted wool has potential for roadside reclamation use as an ECB or weed mat.

3.1.3.3 Wool Batting, Sugar Loaf Wool Mill and Thirteen Mile Wool Company, Montana

Wool batting is a roll or sheet of wool fiber. The wool is washed and scoured then put through a carder. The carder can make batts that are a blend of multiple fiber types or a blend of fiber colors. Traditional uses are for mattresses, bedding, upholstered furniture, and insulation.

Two Montana wool mills, Sugar Loaf and 13 Mile make wool batts. The batts produced can be made up to 1.2 meters wide and 0.9 meters long (4 ft x 3 ft). Both companies can produce the batts in a variety of weights and colors (Figure 5). The wool batting has a potential for roadside reclamation use as an ECB when used in conjunction with a natural (i.e., cotton) open mesh retention layer.

3.1.3.4 Noils, Montana Wool Lab, Montana

The process of combing cleans plant matter, dirt, and other foreign substances from the wool. Combing also removes the short and immature fibers called noils. As a noil is a relatively short fiber, the fabric made from noils is weaker and considered less valuable. To spin a uniform worsted yarn, the noil must be removed.

A sample of noils was received from the Montana Wool Lab at Montana State University. The coarse noils are of interest as a low quality wool product that may be able to be incorporated into ECB, mulch or compost materials for roadside reclamation uses.

3.1.3.5 Loam Salvage, Faribault Woolen Mill, Minnesota

Founded in 1865 in Faribault, Minnesota, the Faribault Woolen Mill is an icon of American woolen craftsmanship. Faribault woolens are renowned for their quality woolen blankets. The mill weaves blankets on a loam and uses a polyester fiber to add strength to the woven wool fiber. The mill produces large quantities of loam salvage from the weaving machines. The salvage is woven pieces of wool fabric cut from loams. This loam salvage is a waste material that sells for low cost and has the potential to be re-used in an ECB.

Figure 5: Wool batting produced at Sugar Loaf Wool Carding Mill in Hall, Montana.

3.1.3.6 Washed, Scoured and Shredded Wool, Brookside Woolen Mill, Montana

Washed and scoured wool of 7.6 - 17.8 cm (3 - 7 in) fibers, or cut into shorter fibers, is available at the Brookside Woolen Mill. The color of the wool fibers or the contamination with hair is not important. The long wool fibers have the potential to be mixed with straw to make ECB. It could possibly be a substitute for imported coconut fibers while adding the water holding and nutrient benefits of wool. The loose pieces sell at a relatively low cost and could be added to ECB in a variety of straw/wool ratios. The washed and scoured wool pieces can also be shredded which may be beneficial for incorporation into an ECB (Figure 6).

Figure 6: Washed, scoured and shredded wool sample from Brookside Woolen Mill.

3.1.3.7 Wool / Straw ECB, Ero-Guard Inc., Mapleton, Minnesota

Ero-Guard was founded on the basis of bringing the highest quality and service to the rolled erosion control product industry. Many of their offerings are specific to erosion control including silt fence, wattles, erosion control blankets, and hydroseed mulches. Their ECB manufacturing facility allows them to produce and develop products with a variety of technical specifications. For example, they have produced approved materials for all Minnesota Department of Transportation (DOT) and most Wisconsin DOT categories and classes. Ero-Guard was approached for collaboration in developing a pure wool and wool/straw blends of ECB due to their ability to manufacture ECB and their interest in product research and development (Figure 7 and Figure 8).

Figure 7: Demonstration of two erosion control blankets using different ratios of wool and straw produced by Ero-Guard.

Figure 8: Close-up photograph of a 60 percent wool/40 percent straw erosion control blanket

3.2 Results

3.2.1 Existing Woolen Products Produced Abroad

The New Zealand and English wool products were promising for roadside reclamation uses in Montana. Unfortunately, shipping products to Montana was cost prohibitive. For example, the cost of one roll of 2 m x 50 m (6.6 ft x 164 ft) Cirtex Biowool BW 400 was NZD $400 with a shipping cost of $2,750 NZD. Acquiring adequate amounts of materials in a timely manner would have been cost prohibitive for the project. As a result, our research team elected to work with local wool mills and manufacturers in the U.S. to produce similar products.

3.2.2 Existing U.S. Woolen Products

The sample of Woolch™ received from Grazeland Farms had easily separated fibers and pulled apart easily. While this product may be suitable for small-scale garden use, it would not be durable enough for large-scale roadside applications.

The 1.9 cm (¾ in) blow-in insulation produced at Brookside is composed of short wool fibers that could possibly enhance wood compost. Blower trucks apply wood-based mulch and this is a common practice for highway reclamation projects by MDT and other state highway agencies. The research team selected to test applications of adding wool fibers to standard compost used by MDT. To test wool as a compost additive, initially the research team will need to investigate the appropriate ratio of wool:compost suitable for roadside applications (Table 2).

3.2.3 New Woolen Reclamation Products

Wet felted wool from Sugar Loaf and needle felted wool from Brookside were selected for further testing and experimentation in the roadside reclamation project. A variety of weights/densities of these products were tested as ECBs, silt fencing or as pieces incorporated into compost. Wool batting produced by 13 Mile were also used and tested in a variety of weights and colors to determine their usefulness as an ECB. Washed/scoured and washed/scoured/shredded wool fibers made by Brookside were selected for testing in an admixture with straw as the filler between layers of sisal netting in the ECBs developed by Ero-Guard.

Two products were not selected for further testing as woolen reclamation products. The noils material appeared to become matted and unsuitable as blow-on compost. The loam salvage was also eliminated from further testing due to the presence of small amounts (<10%) of polyester fibers used in the weaving process that make the produce non-100% biodegradable (Table 2).

Table 2: Summary of wool products reviewed, and those selected for further testing in the project.

Product and Manufacturer	Selected for Preliminary Testing	Comments
BioWool 400, wool matting, Cirtex Ind., New Zealand	No	Cost prohibitive due to shipping
Biomac Woolmulch, Maccaferri, New Zealand	No	Cost prohibitive due to shipping
TerraMat Wool, GeoTech Systems Ltd, New Zealand	No	Cost prohibitive due to shipping
EcoWool Mulch Mat, Advance Landscape Sys, New Zealand	No	Cost prohibitive due to shipping
Wool Mulch Mat, Terra Lana, New Zealand	No	Cost prohibitive due to shipping
Twool, Twool Twine, England	No	Not a suitable product
Thermafleece, Eden Renewable Innovations, England	No	Not a suitable product
Woolch, Grazeland Farm, Minnesota, U.S.	No	Not durable enough for large-scale roadside applications
Blow-in Wool Insulation, Brookside Woolen Mill, MT	Yes	Selected as an addition for compost applications
Wet Felted Wool Batts, Sugar Loaf Wool Mill, MT	Yes	Selected for testing as ECB and silt fence
Needle Felted Wool Batts, Brookside Woolen Mill, MT	Yes	Selected for testing as ECB
Carded Wool Batting, Sugar Loaf Wool Mill and Thirteen Mile Lamb and Wool Company, MT	Yes	Selected for testing as ECB
Noils, Montana Wool Lab, MT	No	Material becomes matted and unsuitable for compost addition
Loom Salvage, Faribault Woolen Mill, MN	No	The woven pieces have a non-biodegradable fiber
Washed/Scoured Wool, Brookside Woolen Mill, MT	Yes	Selected for testing as a component of an ECB
Wool / Straw ECB, Ero-Guard, Mapleton, MN	Yes	Selected for testing as ECB

3.3 Preliminary Field Trials

Based on the evaluation of the sixteen wool products from around the world, the research team worked with the three Montana wool mills to develop and manufacture a variety of select wool fabrics that were considered to be the most promising for roadside reclamation products – erosion control blankets, ditch liners, silt fences or wool as an additive to wood-derived compost (Table 3). Three different wool fabric manufacturing methods – carding, wet felting, and needle punch felting - were used to create 1 m x 1 m (3.3 ft x 3.3 ft) test batts of material for preliminary testing. In addition, after exploration of the appropriate amount of wool to add to wood compost was completed, two ratios of scoured wool:compost were created to test in 1 m by 1 m test plots.

Table 3: Woolen products identified for preliminary field trials.

Woolen Product	Source
407 g/m^2 (12 oz/yd^2) wet felted wool batt	Sugar Loaf Wool Mill
203 g/m^2 (6 oz/yd^2) wet felted wool batt	Sugar Loaf Wool Mill
68 g/m^2 (2 oz/yd^2) carded wool batt (dark and grey)	Thirteen Mile Lamb and Wool Company
136 g/m^2 (4 oz/yd^2) carded wool batt (dark and grey)	Thirteen Mile Lamb and Wool Company
203 g/m^2 (6 oz/yd^2) carded wool batt (dark and grey)	Thirteen Mile Lamb and Wool Company
271 g/m^2 (8 oz/yd^2) carded wool batt (dark and grey)	Thirteen Mile Lamb and Wool Company
40:1 compost:scoured & cut wool (1.9 cm (0.75 in))	Brookside Woolen Mill
20:1 compost:scoured & cut wool (1.9 cm (0.75 in))	Brookside Woolen Mill
Single layer, single pass, needle felted wool batt	Brookside Woolen Mill
2 crossed layers, double needle felted wool batt	Brookside Woolen Mill
½ layer – 4 times needle felted wool batt	Brookside Woolen Mill

Similar to the ECBs from New Zealand - Biomac Woolmulch and the Terramat Wool system - the research team was aware that wool fabric by itself would most likely not have the strength necessary to replace standard short-term ECB, ditch liner or plastic silt fence materials currently used by MDT and other transportation agencies. The Biomac Woolmulch and the Terramat Wool system's manufacturers offered options to add fibers or mesh to the wool matts to give them the appropriate tensile strength to withstand steep slopes, endure for at least one to two years and control erosion.

The Montana wool mills did not have the appropriate equipment or machinery to add natural or synthetic fibers to their wool products, to enhance the woolen fabrics with various stitching patterns or to apply layers of natural or synthetic mesh to the wool product. Thus, our preliminary field trial focused on the amount of wool and the type of manufacture process of the wool mat that would be most successful for roadside applications. The manufacture of the ultimate wool reclamation product, its ability to meet FHWA specifications for the category of product it seeks to replace (i.e., ECB, silt fence), and the appropriate type of strengthener to use with the wool in the manufacturing process was not the focus of the preliminary field trials. Those concerns were addressed after the wool ECB performance is evaluated.

The focus of the preliminary field tests was to determine if the weight, color, or the method used to create the wool fabric (i.e., carding, needle punching) would promote or impede seedling germination or growth through the material. A series of side-by-side plots were established in a private field south of Bozeman in the summer of 2014. Individual test plots, each 1 m^2 (3.3 ft^2) in size, were established in rows and a typical MDT seed mix of perennial grasses (Table 4) was hand broadcast on each test plot before the woolen batts or mulch was applied. The seed mix was given to the project by MDT and bought from Bruce Seed Farm, Inc., Townsend, Montana. Prior to installation, the area was cleared of vegetation using glyphosate (Roundup®) and raked to create good seed to soil contact.

Table 4 : Typical MDT perennial grass seed mix and seeding rate used for preliminary test plots.

Common Name	Scientific Name	Seeds/lb	Rate (PLS lbs/acre)	Seeds/ft^2	Percent of Mix	Rate: (PLS g/m^2)
Sheep Fescue	*Festuca ovina*	680,000	2.5	39	29%	0.28
Thickspike wheatgrass	*Elymus lanceolatus spp lanceolatus*	154,000	2.5	9	29%	0.28
Canada wildrye	*Elymus canadensis*	115,000	2.5	6	29%	0.28
Canada Bluegrass	*Poa compressa*	2,500,000	1.25	70	14%	0.14
		Total	8.75	124	100%	0.98

All test plots were constructed near Bozeman, MT, on 10 June 2014, except for the needle felted products which were installed 8 September 2014. Each woolen product had one replication. In addition, the carded wool batting had a dark and light grey color version per product (Figure 9). Wool products were secured on each test plot with mesh netting and sod staples.

Figure 9: Field trial set-up to identify the products for large-scale testing.

3.3.1 Results of Preliminary Field Trials

The test plots were visually assessed for their ability to provide ground cover and allow seedling establishment and penetration of the woolen material (Figure 10). In general, the color of the wool batting did not impact seedling establishment. Therefore, dark wool batts could be used for the project's two year field trials, which was beneficial because they more closely resembles soil colors and are less expensive than white wool. We found the denser wool products (203 g/ m^2 – 407 g/m^2 (6 oz/yd^2 - 12 oz/yd^2)) did not readily allow seedling penetration. Instead, the seedlings lifted these thicker wool products from the soil surface decreasing their ability to retain soil and moisture, nor prevent erosion. Therefore, the wet felted wool batt (407 g/m^2 (12 oz/yd^2)), and the 203 g/m^2 (6 oz/yd^2) and 271 g/m^2 (8 oz/yd^2) carded batts were eliminated from the subsequent two year field trials of Chapter 5 (Table 5).

Figure 10: Seedlings are able to penetrate the 68 g/m^2 and 136 g/m^2 carded wool batting (left), but had difficulty penetrating the 203 g/m^2 and 271 g/m^2 carded wool batting (right).

3.4 Geotextile Manufacturing

In the fall of 2014 and winter of 2015, the research team explored the potential of engaging a manufacturer of rolled erosion control materials that also supported re-vegetation. We contacted Ero-Guard of Mapleton, Minnesota which makes many different standard ECB products that are deployed in Montana and other northern states (i.e., Minnesota, North Dakota, and Wisconsin). The research team was interested in Ero-Guard because of their experience in making short-term (1-2 years) rolled ECBs, and sought their support in developing prototype woolen ECBs for the research project (Ero-Guard 2015).

As part of this exploration of potential wool ECBs, Brookside in Malta, Montana was the only large facility to scour (clean) wool for use by other businesses. For example, they currently scour wool for use as a natural, hypoallergenic blow in insulation and this is marketed and sold as Green Montana Wool Insulation (Montana Green Insulation 2011). The insulation is washed/scoured and then cut to lengths of approximately 1.9 cm (3/4 in). These short wool fibers are then shredded. Brookside also makes the precursor to this product which is washed/scoured 1.9 cm (3/4 in) wool fibers. These two types of fibers were the wool material Ero-Guard thought might be possible to use in its ECB roller machinery and could be mixed with straw.

Table 5: Summary of wool materials developed for silt fence, rolled erosion control blanket or as an additive to wood compost and selected for field tests.

WEIGHT and PURPOSE	WOOL MANUFACTURE METHOD	PRODUCT MANUFACTURER	PRELIMINARY FIELD TEST CONDUCTED	SELECTED for FIELD TESTING	COMMENT
Silt Fence					
407 g/m^2 (12 ounces (oz)/yard (yd) ^{2}) batt	Wet Felt	Sugar Loaf Wool Mill	No	Yes	Highest tensile strength of all pure wool materials
407 g/m^2 (12 oz/yd^2) batt (2-6 oz pieces combined)	Wet Felt	Sugar Loaf Wool Mill	No	Yes	Will require additional fibers/treatment to provide strength
Extended Term Erosion Control Blanket (ECB)					
203 gram (g)/meter (m)^2 (6 oz/yd^2) batt	Wet Felt	Sugar Loaf Wool Mill	Yes	No	Suppresses seedlings
407 g/m^2 (12 oz/yd^2) batt	Wet Felt	Sugar Loaf Wool Mill	Yes	No	Suppresses seedlings
272 g/m^2 (8 oz/yd^2) batt	Card	Thirteen Mile Lamb and Wool Co.	Yes	No	Partially suppresses seedlings
203 g/m^2 (6 oz/yd^2) batt	Card	Thirteen Mile Lamb and Wool Co.	Yes	No	Appears to slightly suppresses seedlings
136 g/m^2 (4 oz/yd^2) batt	Card	Thirteen Mile Lamb and Wool Co.	Yes	Yes	Light weight allowed better seedling penetration
68 g/m^2 (2 oz/yd^2) batt	Card	Thirteen Mile Lamb and Wool Co.	Yes	Yes	Light weight allowed better seedling penetration
Single layer wool carded batt, one pass thru needle punch	Needle Punch	Brookside Woolen Mill	Yes	Yes	Strong but light weight
Single layer carded wool batt, two crossed passes thru needle punch	Needle Punch	Brookside Woolen Mill	No	No	Little difference to one pass material
One half layer carded wool batt, four crossed passes thru needle punch	Needle Punch	Brookside Woolen Mill	No	Yes	Closest product to New Zealand's BioWool 400 sample
Pure wool filled ECB	Scour & Cut	Ero-Guard Inc.	No	No	Standard ECB machinery does not incorporate cut wool well
Pure wool filled ECB	Scour, Cut & Shred	Ero-Guard Inc.	No	Yes	Standard ECB machinery can use this wool product the best
70% wool : 30% straw filled ECB	Scour, Cut & Shred	Ero-Guard Inc.	No	Yes	Not sure if pure wool needed, so trying different ratios
50% wool : 50% straw filled ECB	Scour, Cut & Shred	Ero-Guard Inc.	No	Yes	Not sure if pure wool needed, so trying different ratios
30% wool : 70% straw filled ECB	Scour, Cut & Shred	Ero-Guard Inc.	No	Yes	Not sure if pure wool needed, so trying different ratios
Wool Compost Enhancement					
40:1 by weight, wood compost : scoured & cut wool, 1.9 centimeters (0.75 inch)	Scour & Cut	Glacier Gold Compost: Brookside Woolen Mill	Yes	Yes	Appears to be ideal ratio
20:1 by weight, wood compost : scoured & cut wool, 1.9 centimeters (0.75 inch)	Scour & Cut	Glacier Gold Compost: Brookside Woolen Mill	Yes	No	Too much wool in mix

Ninety-one kilograms each of the two scoured wool products were used for experimentation in the winter of 2015. Ero-Guard investigated how each of the two wool products performed in their ECB roller and machinery (Figure 11). They also experimented with different proportional mixes of wool and straw. Ero-Guard determined that the best wool product to use in the ECB roller was the 1.9 cm cut and shredded product from Brookside. Ero-Guard made a variety of wool ECB prototypes including pure wool and 30:70 wool:straw ratios in the ECB fill. The fill material is approximately 542 g/m^2 (1 pound/yd^2) of material. Thus, pure wool short-term rolled ECB would contain approximately 542 g/m^2 (16 oz/yd^2) and 50:50 wool:straw would contain approximately 271 g/m^2 of wool and 271 g/m^2 of straw (8 oz/yd^2 of wool and 8 oz/yd^2 of straw).

Ero-Guard discovered that its machinery readily accepted wool in its hoppers and that they could mix straw and wool at different ratios (Figure 11) particularly if they had Brookside’s cut and shredded wool product. They conducted a process of trial and error to become familiar with how the wool behaved in the roller machinery and how to get it into a mixture with the straw. A Ero-Guard business partner stated that it only took one hour to convert the ECB roller operation from its standard manufacturing function to one that could use wool.

Figure 11: Ero-Guard experimenting with a wool-straw combination for fill in a rolled erosion control blanket.

The results of the experimentation were rolls of ECB of different wool and straw ratios. These rolls were sent to the WTI research team for their review. The research team and a representative of MDT found the products to be very similar in appearance and function to standard short-term ECB rolls. It was observed that there were a variety of mixes of wool and straw as fill, but it was the two external mesh layers that give the material its strength. Thus, pure wool and wool:straw of different ratios that filled the experimental ECBs could be installed and secured on roadside slopes exactly the same as standard rolled short-term straw fill ECB materials.

As a result of the success of Ero-Guard's experimental production, the research team ordered an additional 363 kg (800 lb) of 1.9 cm (3/4 in) cut and shredded wool from Brookside and had it shipped to Ero-Guard. Ero-Guard made materials for the two-year field tests and laboratory tests (Table 5).

3.5 Recommendations

The product search and preliminary field trials during the summer of 2014 identified eight pure wool products with the highest potential to improve roadside reclamation efforts for MDT and other transportation agencies. These wool materials occur in three types of reclamation material: 1) erosion control blanket, 2) silt fence, or 3) an additive to wood derived compost (Table 6).

The woolen products developed and selected for prototypes of woolen ECBs are the 68 g/m^2 and 136 g/m^2 (2 oz/yd^2 and 4 oz/yd^2) carded wool batts, and three different types of needle punch felted wool batts. The sixth potential wool product, to be used primarily for seedling establishment, is standard compost with a cut wool additive at a ratio of 40 (moist weight) compost: 1 (dry weight) scoured and cut wool. This same material can be used solely for seedling establishment, that is, on flat or low-grade roadsides where erosion is not a concern (Table 6).

Lastly, wool silt fence prototypes were developed and tested using wet felted wool at two densities: 203 g/m^2 and 407 g/m^2 (6 oz/yd^2 and 12 oz/yd^2; Table 6). It was unclear if felted wool at either density would be strong enough to withstand storm events and surface runoff as silt fence. These wool products had the least prospects of success of all the wool reclamation prototypes developed by the project, without further development with the manufacturing sector to give them the required strength needed to withstand storm events.

Table 6: Woolen silt fence and erosion control fabrics identified for lab and field tests.

Woolen Product	Source	Product Use
407 g/m^2 (12 oz/yd^2) wet felted wool batt	Sugar Loaf Wool Mill	Silt fence
203 g/m^2 (6 oz/yd^2) wet felted wool batt	Sugar Loaf Wool Mill	Silt fence
68 g/m^2 (2 oz/yd^2) carded wool batt (dark and grey)	Thirteen Mile Lamb and Wool Company	ECB and seedling establishment
136 g/m^2 (4 oz/yd^2) carded wool batt (dark and grey)	Thirteen Mile Lamb and Wool Company	ECB and seedling establishment
40:1 compost:scoured & cut wool (1.9 cm (3/4 in))	Brookside Woolen Mill	Seedling establishment
Single layer, single pass, needle felted wool batt	Brookside Woolen Mill	ECB and seedling establishment
2 crossed layers, double needle felted wool batt	Brookside Woolen Mill	ECB and seedling establishment
½ layer – 4 times needle felted wool batt	Brookside Woolen Mill	ECB and seedling establishment

The ECB products developed with a geotextile manufacturer in Minnesota, using washed/scoured/shredded wool from a Montana mill, were mixed at various ratios with straw to produce five products for field and laboratory tests (Table 7). Their wool-straw ratios were varied to determine if lower amounts of wool (reducing ECB production costs) perform equal to, or better than, ECBs with higher amounts of wool.

Table 7: Rolled erosion control blankets manufactured for lab and field tests.

Woolen Product	Source	Product Use
100% wool filled ECB	Ero-Guard	Erosion control and seedling establishment
70% wool / 30% straw ECB	Ero-Guard	Erosion control and seedling establishment
60% wool / 40% straw ECB	Ero-Guard	Erosion control and seedling establishment
50% wool / 50% straw ECB	Ero-Guard	Erosion control and seedling establishment
30% wool / 70% straw ECB	Ero-Guard	Erosion control and seedling establishment

4 LAB TESTS

Lab tests were necessary to evaluate the effectiveness of woolen roadside reclamation products to meet the specifications required by MDT so that they can be used by the agency. If the project is to develop and test potential wool products that can be easily produced as complementary or replacement products for existing roadside reclamation and best management practices, that requires they meet particular performance specifications. The research team, in coordination with the project's Technical Advisory Committee, selected laboratory tests for the most promising wool products (see Chapter 2) to assure they meet specifications for MDT and Federal Highway Administration (FHWA) deployment.

The primary objective of the lab tests is to evaluate key geotextile material characteristics and the nutrient content of the woolen products developed by this project, as well as those of the standard reclamation erosion control products. The tests seek to compare existing specifications of roadside reclamation products to their woolen equivalents. The results will assure transportation agencies that woolen materials developed by the project meet or exceed the specifications of comparable existing reclamation products.

First, the research team collected required specifications of products from MDT. Then, the research team, working with the Technical Advisor Committee and Western Transportation Institute's (WTI) geotextile specialist, sent samples to a commercial lab to evaluate whether the woolen erosion control products met minimum required material properties outlined in Montana's *Standard Specifications for Road and Bridge Construction*. Specifically, the commercial lab evaluated tensile strength (ASTM D4595), performance in protecting hillslopes from rainfall-induced erosion (ASTM D6459), and performance in protecting earthen channels from stormwater-induced erosion (ASTM D6460).

Lab tests of woolen and standard reclamation product chemical and physical characteristics were also deemed important to measure as a tool to compare the benefits of woolen products to standard materials. These tests determined whether wool was providing additional macro- or micro-nutrients or increased water holding capacity compared to standard products.

The wool silt fence products developed for this project were not developed to the stage of full scale deployment or commercialization. It was decided that the use of limited project funds to test the wool silt fence was not an efficient or effective use of limited funding.

4.1 Lab Tests

4.1.1 Standardized Laboratory Tests

The project developed new wool ECB products that have not been described according to the MDT Manual's categories (short- or long-term blanket) or performance standards. The wool products use needs to be specified in standard provisions such as coir netting products and hybrid blankets. These categories include product types that can be applied to over 95% of the sites and conditions that MDT would use an ECB or matting. (per. comm., Phil Johnson, MDT Reclamation Specialist). Lab tests were selected based on specifications and performance attributes that influence overall function of the ECB. Test methods and specifications evaluated during this project were provided by MDT for rolled ECBs and are generally the same as those contained in the MDT Manual, with the exception of mass per unit area. Laboratory tests for the wool/straw ECB developed by this project were selected based on requirements in MDT's Manual, *Standard Specifications for Road* *and Bridge Construction* (MDT Manual including the *Supplemental Specifications*) and the number of replications were limited by the costs for the tests. The MDT Manual has three performance attributes for temporary rolled erosion control products-type III; they are minimum tensile strength, maximum "C" factor (soil loss), and minimum shear stress tests (MDT 2014). Cost estimates were obtained from two laboratories: Testing, Research, Consulting and Field Services (TRI Environmental, Inc.) and Geo Testing Express.

The selected standardized laboratory tests for the wool/straw ECB are defined as follows:

1) <u>Mass per unit area</u> of the combined fiber matrix and netting (g/m^2): A measure of the bulk of the matrix and netting/stitching.
2) <u>Tensile strength – machine direction</u> (kg/m^2): A measure of the strength of the materials used in the blanket's netting and stitching. The purpose of the netting/stitching is to hold the matrix in place. The stronger the netting/stitching, the longer the matrix remains in uniform distribution.
3) <u>C Factor (measured shear strength @ loss of 0.5 inch (1.27 cm) of soil</u> (kg/m^2): A measure of the ability of the blanket to protect the soil resource beneath the blanket.
4) <u>Minimum shear strength – un-vegetated condition</u> (kg/m^2): A measure of the strength of the blanket to withstand surface flow forces.

The results of the laboratory tests were used to compare wool ECB products to the standard ECB products, MDT performance standards, and MDT terms.

4.1.2 Analytical Laboratory Tests

Roadside reclamation products containing wool may perform similarly or better than existing commercially available products. Since scoured wool can store up to 400% of its weight in water (Upton 2003), it was hypothesized that woolen ECBs may provide exceptional soil moisture retention to aid in plant growth. Therefore, testing water holding capacity of woolen products in comparison to current standard products was a worthwhile pursuit. In addition, sheep wool contains up to 17% nitrogen and thus can be considered a "fertilizer" for plant growth and development as it decomposes. Thus, in addition to ECB performance tests, analytical tests were selected to characterize the nutrient content and water holding capacity for felted wool matts, 100% rolled wool ECB, straw/coconut rolled ECB and compost. The former two products were developed by the project; the latter two products are the standard products uses as controls for field experimentation.

4.2 Materials and Methods

While various performance values of wool have been described in published literature that document the benefits of wool products, such as their strength and durability, water holding capacity and nutrient value; the capabilities of the new woolen roadside revegetation products developed by this project were unknown. Therefore, laboratory tests were used to quantify particular attributes of the woolen products and to use these values to compare to standard reclamation products used by MDT and other transportation agencies.

4.2.1 Standardized Laboratory Tests

Physical property testing was performed including measurement of mass per unit area of the newly developed wool reclamation products used in this study. The manufacturers of pure wool ECBs and wool/straw ECBs estimated the weight and proportion of wool and other components in each product and labeled them accordingly. We quantified the total mass of each product as well as the amount of wool in each product which is similar to ASTM D6457, a standard of the American Society for Testing and Materials (ASTM). ASTM D6457 is the standard test method for measuring mass per unit area of ECBs. Mass per unit area was measured by subsampling five 10 cm^2 pieces of each product and weighing each sample and calculating their mean weight.

Material lab testing methods for geotextile fabrics for use in slope stabilization and erosion control followed standard ASTM testing methods. The number of wool/straw products and replications tested was dependent on available project funds. Testing requirements followed MDT's *Standard Specifications for Road and Bridge Construction*, 2014 edition. Page 503 of this MDT publication includes Table 713-5, which lists the following standards for "Temporary Rolled Erosion Control Property Requirements": ASTM D4595, minimum tensile strength, ASTM D6459, maximum C Factor (soil loss) and ASTM 6460, minimum shear stress.

Due to the high cost of lab tests and the limited funds, only one product and one replication of tensile strength, C factor, and shear stress was ordered from the lab (Table 8). The wool product tested was the 50% wool / 50% straw ECB because it is similar to the standard 70% straw / 30% coconut ECB currently used on most MDT roadside revegetation projects and was the product used as a control for the field experiments. Also, there were adequate quantities of these two products needed for laboratory testing. The 50% wool / 50% straw ECB was tested at TRI Environmental, Inc.'s (TRI) laboratory during summer 2016 for minimum tensile strength (ASTM D 4595), maximum C factor (ASTM D 6459) and minimum shear stress (ASTM D 6460). The 70% straw / 30% coconut ECB control product (Ero-Guard) was tested at TRI Environmental Laboratory in 2007 for tensile properties (ASTM D 6818).

Table 8: The products and lab tests evaluated.

Wool Product	Test	Purpose	Replication	Lab
50% Straw / 50% Wool ECB	ASTM D4595	Minimum tensile strength	1	TRI
50% Straw / 50% Wool ECB	ASTM D6459	Maximum "C" Factor (soil loss)	1	TRI
50% Straw / 50% Wool ECB	ASTM D6460	Minimum shear stress	1	TRI

4.2.2 Analytical Laboratory Tests

To aid in understanding the nutrient and water holding capacity benefits of the wool in each product, the woolen products were sent for laboratory tests for a suite of nutrients and water holding capacity measurements using standard lab methods at Energy Laboratory in Helena, MT (Table 9). Also, the standard straw/coconut ECB was sent for the same tests, for comparison purposes. The nutrient and water capacity tests (Table 9) were selected for their ability to influence seedling establishment and plant growth. These are common tests used by transportation departments to evaluate roadside soils before developing reclamation plans.

The following four products were tested:

1. Wool batt, which is a pure wool ECB derived from scoured wool that is subsequently carded and then felted by agitating in water.
2. Scoured wool, this product was used both at different ratios in the various rolled straw/wool ECBs and was added to the wood-based compost.

3. The standard rolled straw/coconut ECB, which is used as a control in field experiments.
4. A typical wood-based compost, which is used as a control in field experiments.

Table 9: Analytical methods for products and soil samples.

Measure of Interest	Analysis
pH (acidity level)	Saturated Paste
Electric Conductivity (EC)	Saturated Paste
Sodium Adsorption Ratio (SAR)	Calculation
Calcium (Ca)	Saturated Paste
Magnesium (Mg)	Saturated Paste
Sodium (Na)	Saturated Paste
Organic Matter (OM) Organic Carbon (OC)	Walkley-Black
Potassium (K)	NH_4OAC Extractable
Phosphorus (P)	Olsen Extract
Nitrate (NO_3)	KCl Extract
Total Kjeldahl Nitrogen (TKN)	TKN Prep
Nitrogen (N), Total	Calculation
Carbon:Nitrogen (C:N) Ratio	Calculation
Percent Saturation	Pressure Plate
Water Holding Capacity (WHC)	Pressure Plate

4.3 Results

The laboratory bench test results identified attributes of the woolen products that are important for determining their success as viable commercial products. Lab results also compared and contrasted wool product attributes with standard industry products that are currently standard products being used by MDT and other agencies.

4.3.1 Standardized Laboratory Tests

4.3.1.1 Mass per Unit Area

Product mass (g/m^2), also referred to as area density, was measured for the newly developed wool reclamation products used in this study. Mass per unit area was determined for the wool reclamation products field tested on the US Highway 287 test site near Three Forks, MT, the wool silt fence that was field tested along U.S. Highway 14 near Martinsdale, MT, and the wool/straw ECBs field tested at the WTI's Transcend 2:1 (V:H) test slope near Lewistown, MT (Table 10).

Three different wool silt fence products, two carded pure wool blankets, and the four-pass needle punched pure wool blanket were tested for mass per unit area (Table 10). Table 10 provides the average weight of each product, and Table 11 provides a new naming convention for each product that will be carried through the remainder of this report. The light weight felted wool and wool/burlap silt fence had relatively even distribution of woolen material throughout each product.

The heavier weight felted wool silt fence was highly variable in the mass per unit area of wool with some areas having twice the area density as other areas within the same product (Table 11). This most likely is a result of its manufacturing process, since this product was felted by agitating in a water tank (wet-felted) which has little quality control. Similarly, the heavier weight carded wool blanket had high variability area density compared to the lighter weight carded wool blanket. Carding is the first process in the felting process of wool where the fibers are aligned, and thus is not usually considered a "finished product". All developmental products had a lower mass per unit area than originally described during the manufacturing phase of the project (Table 10 and Table 11).

The wool/straw ECBs made by Ero-Guard were manufactured and named according to the estimated ratio of wool to straw used for each ECB. The mass per unit area tested the accuracy of the naming convention and identified the true proportions of wool to straw in each product (Table 10). The mass of each component varied by as much as two times the weight in replications of the same product indicating that the wool and straw were not evenly distributed. This is understandable, given this was the first time Ero-Guard used its machinery to produce the variety of wool-straw rolled ECB products. The company and its technicians had to experiment with its machinery since it had never used wool (nor was designed to use wool) before this project. Control of the flow of wool and straw from the hoppers was particularly difficult to meet the desired wool to straw ratios in a consistent manner. This wool-straw mixture flows from the hoppers and is then placed between the two layers of netting and then the unit is stitched together to create the ECB.

Table 10: Mass per unit area of the wool reclamation products[1].

Products	Mass per Unit Area (grams (g)/meter² (m²))					Average Mass (g/m²)	Percent Composition
	1	2	3	4	5		
Wool Silt Fence (400 g/m²)	173	354	169	244	232	234	-
Wool Silt Fence (200 g/m²)	141	145	116	120	180	140	-
Wool / Burlap Silt fence							
Wool Component	188	189	169	234	191	194	-
Burlap Component	348	358	354	361	325	349	-
Carded Blanket (136 g/m²)	62	47	105	54	99	73	-
Carded Blanket (68 g/m²)	54	32	51	35	49	44	-
Needle Punch Wool Blanket	57	62	89	57	92	71	-
100% Wool ECB							
Wool Component	249	346	371	237	306	302	97%
Straw Component	15	11	14	5	1	9	3%
70% Wool / 30% Straw ECB							
Wool Component	146	168	180	207	178	176	54%
Straw Component	171	169	132	156	135	152	46%
60 Wool / 40% Straw ECB							
Wool Component	153	207	126	159	118	153	47%
Straw Component	176	219	179	180	118	174	53%
50% Wool / 50% Straw ECB							
Wool Component	103	93	105	122	76	100	38%
Straw Component	155	99	176	239	158	165	62%
30% Wool / 70% Straw ECB							
Wool Component	55	60	65	57	60	59	24%
Straw Component	205	327	219	146	195	219	76%
70% straw / 30% coconut (control) ECB[2]							
Straw / coconut combined	306	448	324	333	250	332	-

[1]See the metric conversion table at the beginning of this report.
[2]Data provided by Ero-Guard, Inc. for AASHTO NTPEP Rolled Erosion Control Product (RECP) Test Report, ASTM 6475.

The standard straw/coconut ECB was also variable in the distribution of the two components indicating that even distribution may not be common. The 100% wool ECB was the most accurate description of all the ECB, with 97% wool component. In general, the wool/straw ECBs tended to underestimate the wool component and overestimate the straw component (Table 11). The jute netting component of each blanket was relatively constant as it is the same product used for all the ECBs used in this study.

The results in Table 10 indicate the quantity of wool that is needed per square meter to manufacture the product that was tested by the project. For example, the most wool used by a product developed for the project, the 100% wool ECB requires approximately 300 g/m² of wool (8.8 oz/yd²) or the heavier pure wool silt fence which used 244 g/m² of wool (7.2 oz/yd²). For other objectives of this project, this information will be helpful in evaluating relative costs, since wool is the most expensive raw material, relative to straw and jute, in the erosion control blankets and is an additive to compost.

Table 11: New product naming convention based on the product's actual weight and proportions.

Original Product Name / Description	New Product Name / Measured Description
Wool Silt Fence (400 g/m^2; 12 oz/yd^2)	Wool Silt Fence (244 g/m^2; 7 oz/yd^2)
Wool Silt Fence (200 g/m^2; 6 oz/yd^2)	Wool Silt Fence (140 g/m^2; 4 oz/yd^2)
Wool / Burlap Silt fence	Wool / Burlap Silt fence (194:349 g/m^2; 6:10 oz/yd^2)
Carded Wool Blanket (136 g/m^2; 4 oz/yd^2)	Carded Wool Blanket (73 g/m^2; 2 oz/yd^2)
Carded Wool Blanket (68 g/m^2; 2 oz/yd^2)	Carded Wool Blanket (44 g/m^2; 1 oz/yd^2)
Needle Punch Wool Blanket	Needle Punch Wool Blanket (71 g/m^2; 2 oz/yd^2)
100% Wool ECB	100% Wool ECB
70% Wool / 30% Straw ECB	55% Wool / 45% Straw ECB
60 Wool / 40% Straw ECB	50% Wool / 50% Straw ECB
50% Wool / 50% Straw ECB	40% Wool / 60% Straw ECB
30% Wool / 70% Straw ECB	25% Wool / 75% Straw ECB

4.3.1.2 Tensile Properties

Six replicates were tested to determine the tensile properties of the wool/straw ECB (using ASTM D 4595), and five replicates were tested to determine the tensile properties of the straw/coconut ECB (using ASTM D 6818). The results of these tests are summarized in Table 12. The two products had comparable ultimate strength values in the machine direction (MD); however, the wool/straw ECB had a greater ultimate strength in the cross-machine direction (XMD). The percent elongation was two and five times lower for the wool/straw ECB than the standard ECB indicating that the wool product is stiffer than the coconut/straw product.

Table 12: Results of the tensile property tests for the wool/straw and straw/coconut erosion control blankets.

Product and Laboratory Test	Replicate[1]						Mean
	1	2	3	4	5	6	
40% Wool / 60% Straw ECB (previously called) 50% Wool / 50% Straw ECB (ASTM D 4595)							
MD- Ultimate Strength (kilogram/meter ((kg/m))	350	348	407	375	257	371	**351 kg/m**
XMD – Ultimate Strength (kg/m)	182	302	177	302	196	220	**230 kg/m**
MD – Elongation @ Ult. Load (%)	11.8	7.34	5.85	8.37	13.3	7.34	**9.0 %**
XMD – Elongation @ Ult. Load (%)	8.74	7.10	5.33	5.77	3.03	7.71	**6.3 %**
70% Straw / 30% Coconut ECB (ASTM D 6818)[3]							
MD- Ultimate Strength (kg/m)	350	451	430	336	395	-	**392 kg/m**
XMD – Ultimate Strength (kg/m)	173	173	170	175	184	-	**175 kg/m**
MD – Elongation @ Ult. Load (%)	17.3	26.0	18.7	22.7	22.0	-	**21.3 %**
XMD – Elongation @ Ult. Load (%)	25.3	35.3	32.7	32.0	29.3	-	**30.9 %**

[1]See the metric conversion table at the beginning of this report.
[2]MD = machine direction; XMD = cross-machine direction.
[3]Data provided by Ero-Guard, Inc. for AASHTO NTPEP Rolled Erosion Control Product (RECP) Test Report.

To determine if the wool ECB met MDT standards, we compared our results to the MDT Temporary Rolled Erosion Control properties for short- and long-term blankets (Table 13 and Table 14). In Table 13 Type II is a short-term (12 month) ECB, and Type III is a long-term ECB (24 months). The wool ECB had an average tensile strength machine direction of 351 kg/m which met MDT standards for a short term (Type II B, C) or long term (Type III A) ECB. The wool ECB also met MDT's updated supplemental specifications of a minimum tensile strength of 190 lbs/ft (Table 14).

Table 13: MDT material specifications for temporary rolled erosion control, 2014. See MDT Materials Specifications Manual, Table 713-5.

TEMPORARY ROLLED EROSION CONTROL								
Property	**Type II**				**Type III**		**Type IV**	**Test Method**
	A[1]	**B**	**C**	**D**	**A[1]**	**B**		
Typical functional longevity[2] (months)	12				24		36	N/A
Minimum tensile stregth[3] lbs/ft^2 (kg/m^2)	5 (24.4)	50 (244.1)		75 (366.2)	25 (122.1)	100 (488.2)	125 (610.3)	ASTM D4595
Maximum "C" factor[4]	0.10 at 1V:5H	0.10 at 1V:4H	0.10 at 1V:3H	0.10 at 1V:2H	0.10 at 1V:5H	0.25 at 1V:1.5H	0.25 at 1V:1H	ASTM D6459
Minimum permissible shear stress[5,6] psf (Pa)	.25 (12)	.50 (23.9)	1.50 (71.8)	1.75 (83.8)	.25 (12)	2.00 (95.8)	2.25 (107.7)	ASTM D6460

[1]Obtain max "C" factor and allowable shear stress for mulch control netting with the netting used in conjunction with pre-applied mulch material.
[2]Functional longevities are for guidance only. Actual functional longevities may vary based on site and climatic conditions.
[3]Minimum average roll values, machine direction.
[4]"C" factor calculated as ratio of soil loss from rolled erosion control product protected slope (tested at specified or greater gradient, v:h). to ratio of soil loss from unprotected (control) plot in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using Erosion Control Technology Council (ECTC) Test Method #2.
[5]Minimum shear stress the rolled erosion control product (un-vegetated) can sustain without physical damage or excess erosion (> ½ inch (13 mm) soil loss) during a 30-minute flow event in large-scale testing. These performance test values should be supported by periodic bench scale testing under similar test conditions and failure criteria using Erosion Control Technology Council (ECTC) Test Method #3.
[6]The permissible shear stress levels established for each performance category are based on historical experience with products characterized by Manning's roughness coefficients in the range of 0.01 to 0.05.

Table 14: Specifications for temporary rolled erosion control materials. See MDT Material Specifications Manual Table 713-4, 2014 supplement.

ROLLED EROSION CONTROL			
Type	**Mass[1] (lbs/Yd)**	**Tensile Strength – MD[2] (lbs/ft)**	**Min. Shear Strength (lbs/ft)**
Short term	0.5	190	1.70[3]
Long term	0.5	190	2.0[3]
High performance	0.6	190	2.25[3]
TRM – natural fiber matrix	0.8	500	10.0[4]
TRM – synthetic fiber matrix	0.5	300	12.0[4]

[1]Combined fiber matrix and netting.
[2]Machine direction.
[3]Minimum shear stress the rolled erosion control product (un-vegetated) can sustain without physical damage or excess erosion (> ½ inch (13 mm) soil loss) during a 30-minute flow event per ASTM D6460.
[4]Minimum shear stress the TRM (fully vegetated) cab sustain without physical damage or excess erosion (> ½ inch soil loss) during a 30-minute flow event per ASTM D6460.

4.3.1.3 C Factor (soil loss)

A single replicate of the C-factor test (ASTM D6459) was conducted using the wool/straw ECB at 5, 10, and 15 centimeters (cm) (2, 3.9, and 5.9 in) rainfall rates. The results from this test are summarized in Table 15. The lab test bed size was 2.4 m-wide and 12-m long (~8 feet x 40 feet) and the slope had a ratio of 3 horizontal units to 1 vertical unit (3H:1V). Each event was twenty minutes in duration. Soil loss was negligible for the 5 and 10 cm rainfall rates but reached 23.7 kilograms (kg) of soil when rainfall was increased to 15 cm (5.9 in) for 20 minutes (Table 15, Figure 12). The single replicate C-factor was 0.060 indicating that it met the requirements of the MDT standard specifications for this material (Table 13 and Table 14). The C-factor of 0.06 is less than the maximum allowed 0.10 for a short-term ECB (Type II C; Table 14). Images of the C-factor test illustrate the wool product was able to control soil loss for the majority of the test slope, with some rills starting after the 15-cm rain event (Figure 12).

Table 15: Results of the maximum C factor (ASTM D 6459) test for 40% Wool / 60% Straw ECB.

Product	Intensity (centimeters/hour)	Runoff (liters)	Cumulative R Factor	Soil Loss (kilograms/plot/event)	Cumulative Soil Loss (tons/acre)	Single Replicate C-Factor
40% Wool /60% Straw ECB	5.2	4.5	6.74	0.0	0.00	0.060
	10.1	340.9	50.42	0.17	0.03	
	15.3	1041.7	163.55	23.65	3.58	

Figure 12: Images of intensities for C factor test (ASTM D 6459) for wool/straw erosion control blankets (photo courtesy of TRI).

4.3.1.4 Shear Stress Test

The minimum shear stress test, ASTM D 6460, modified for a single replication, was conducted in June 2016. The flume size was 0.6 m wide by 12 m long (2 x 40 ft), had a 10% slope, and each event was thirty minutes in duration. The un-vegetated test was conducted at a shear range of 2.4 – 9.8 kg/m^2 (0.5 - 2.0 lbs per square ft (psf)). Shear levels 1 and 2 were tested but levels 3 and 4 could not be run since the erosion threshold of 1.3 cm (0.5 in) had been exceeded (Table 16). The resulting shear stress range for the wool product was 4.3 – 6.5 kgsm (0.9 – 1.3 psf). The 40% wool/ 60% straw ECB exceeded the minimum bed shear stress specified in the MDT standard specifications for short term ECB (Type II B; Table 13) for low level events, but not for high level events. The shear test results were lower than the updated minimum shear stress (1.7 psf) required by MDT for short term ECBs (Table 14). Images of the shear stress test illustrate rills forming the length of the test slope after the low-medium flow event (Figure 13).

Table 16: Results of the minimum shear stress test (ASTM D 6460) for wool/straw ECB.

Shear Level	Depth (cm)	Velocity (mps)[1]	Flow (cms)	Manning's Roughness	Maximum Bed Shear Stress (kgsm; Pa)	CSLI (cm)	Cumulative CSLI (cm)
1	4.3	1.0	0.03 cms	0.039	4.3 kgsm 42.2 Pa	0.4 cm	0.4
2	6.4	1.6	0.06 cms	0.032	6.5 kgsm 63.7 Pa	1.4 cm	1.8
3	Higher flow not run since erosion threshold of 1.3 cm (0.5 in) was exceeded.						
4	Higher flow not run since erosion threshold of 1.3 cm (0.5 in) was exceeded.						

[1] Units are as follows: mps = meters per second; cms = cubic meters per second; kgsm = kilograms force per square meter; Pa = pascal (for comparison to MDT standards); CSLI: Clopper soil loss index.

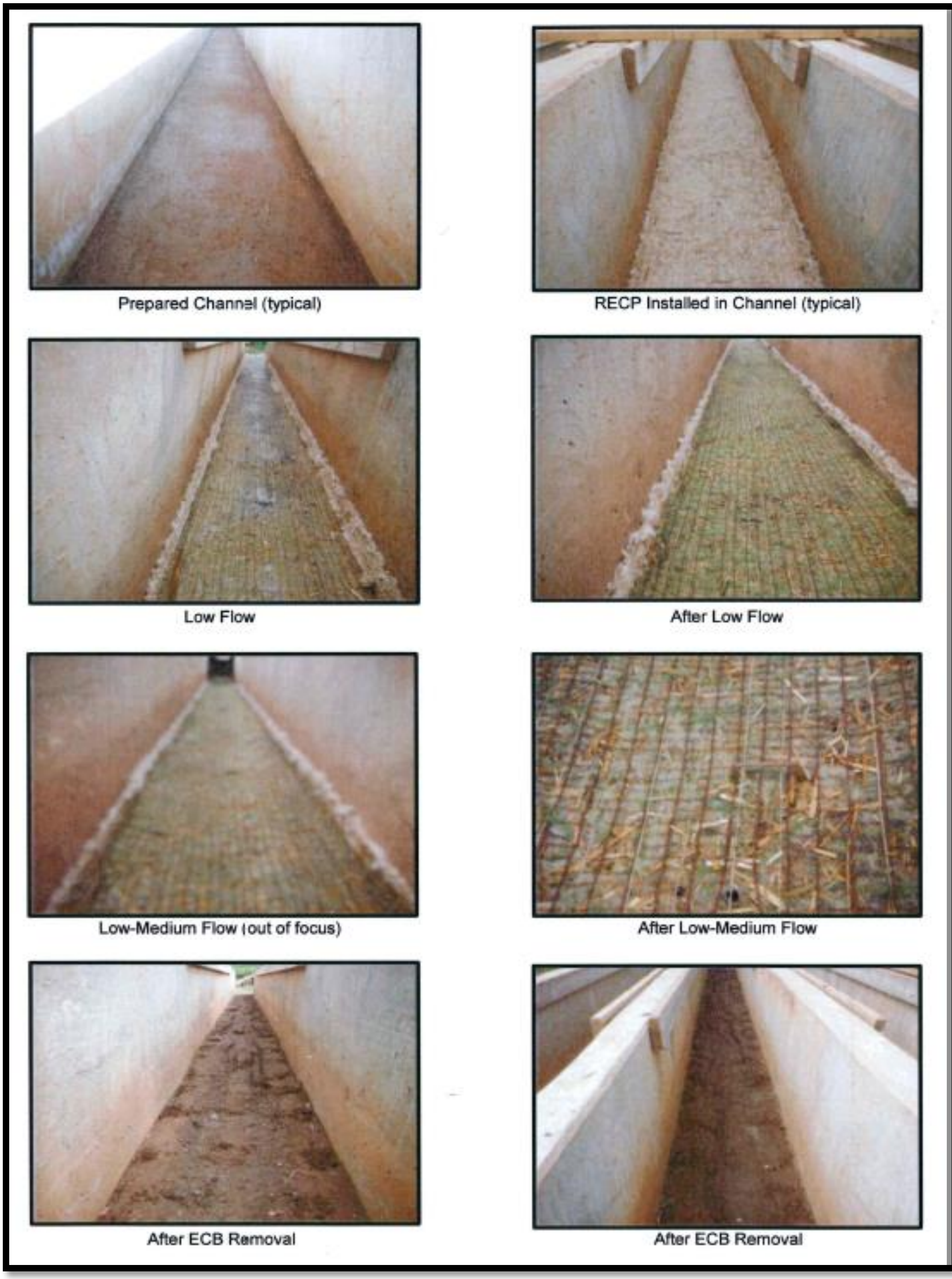


Figure 13: Images of flow levels for minimum shear stress (ASTM D 6460) test for wool/straw ECB (photos courtesy of TRI).

4.3.2 Analytical Laboratory Tests

Laboratory tests of the nutritional, water holding capacity and related chemical characteristics of wool and standard reclamation products provided varying results (Table 17). Note that the chemical analytical tests applied to the products used in this research study are designed for soil and not specifically for ECBs, so some measure of caution is warranted in interpreting the results. For example, the pH of the wool products was slightly basic, straw was neutral, and compost was slightly acidic. The acidity of compost is most likely a result of it being comprised of decomposing coniferous wood products and animal manure.

Table 17: Analytical test results for the product materials and study site soil.

Analytical Test[1]	Material Tested			
	Wool Batts	Scoured Wool	Straw/Coconut ECB	Wood–based Compost
pH	8.2	7.8	6.7	5.0
EC (dS/m)	0.1	0.3	1.8	2.7
SAR (unitless)	8.9	1.7	0.4	0.8
Ca (mg/L)	0.5	23	11.6	130
Mg (mg/L)	0.5	9.2	9.4	108
Na (mg/L)	29	37	7.6	55
OC (%)	57	57	56	44
OM (%)	99	98	96	76
K (mg/kg)	38	212	14,500	3,770
P (mg/kg)	<5	41	140	640
NO_3, (mg/kg Dry)	13	14	11	300.0
TKN (mg/kg)	92,900	147,000	1,240	4,720
N-Total (mg/kg)	150,000	150,000	1,300	5,000
N-Total (%)	15.0	15.0	0.1	0.5
C:N Ratio	3.8	3.8	429	88
Saturation (%)	787	943	867	318
WHC 0.33 Bar Moisture (wt%)	81	55	150	120
WHC 1.0 Bar Moisture (wt%)	93	73	160	84

[1]Unites area as follows: dS/m=deciSiemen/meter; mg/L = milligrams per liter; % = percent; mg/kg = milligrams per kilogram; WHC = water holding capacity; wt% = percent by weight

The electrical conductivity (EC) test measures soil salinity or soil salt content. Low levels of salinity (< 4.0 deciSiemen/meter) were observed in all products, however the straw coconut ECB exhibited the highest level of salinity (2.7 deciSiemen/meter). Sodium adsorption ratio (SAR), which reports sodium (Na) quantities relative to a combination of calcium (Ca) and magnesium (Mg), suggests that the there is some variability between the Ca, Mg and Na levels in scoured wool versus carded wool resulting in a comparatively elevated SAR of 8.9 in the carded wool primarily due to the low Ca and Mg levels.

The scoured wool had higher Ca, Mg, and Na values than the wool batting. This may be a result of the additional processing that the batts of wool received – they were scoured, then wet felted in an agitated tub of water which would further removes and leaches nutrients from the raw wool.

The straw ECB had moderate levels of Ca, Mg and Na but much less than the compost which was nutrient rich. The percent carbon and organic matter were as anticipated for the product materials.

The number of macronutrients – nitrogen (N) phosphorous (P) and potassium (K) – measured in the products were often surprising (Table 17). Potassium was low in the wool products, but high in the compost and elevated in the straw ECB indicating high amounts of K available for plant uptake in the standard products compared to the experimental wool products. Phosphorous was also lowest in the wool batting and highest in the wood-based compost. The scoured wool had higher P and K values than the wool batting. Wool fiber has no P or K, so the small amounts recorded in the bench tests for wool products are most likely derived from impurities in the wool (i.e., sheep manure, plant material) left after the scouring and/or wet felting processes.

Nitrate (NO_3) is the form of nitrogen that can be readily absorbed by plants for growth and levels were low and similar among the wool batting, scoured wool and straw ECB. Therefore, even though wool fiber is comprised of appreciable total nitrogen, it is not available for plant growth until it is decomposed. Therefore, the impact of wool's potential nitrogen fertilizing effect will be dependent on the amount of wool material applied to a unit area of soil and the amount of time that it takes for each product to decompose. Compost NO_3 levels were approximately three hundred times higher than the other products indicating it is capable of providing N for plant growth immediately after its application.

The wool materials had 15% total nitrogen (total N) which is comprised of all forms of nitrogen. Total N was much greater in the wool products than the straw ECB or the compost suggesting the wool may provide a long-term source of nitrogen fertility. Similarly, the low carbon to nitrogen ratio (C:N) values in the experimental wool products compared to the control products indicates much more nitrogen should be available for plant growth over time.

The three major cations that have a basic or alkaline reaction (K, Ca and Mg) are combined in the measure of saturation or percent base saturation. Base saturation is a measure of the product's or a soil's ability to provide plant nutrition. The percent saturation was high for all products but highest in the scoured wool. The straw ECB control had higher saturation than the wool batting.

In general, the two standard materials currently used by MDT (straw/coconut ECB and compost) had higher water holding capacity than the wool products. Saturation and water holding capacity (WHC) are interpreted together. Water holding capacity is the total amount of water a soil (or material tested) can hold at capacity given soil matric potential measured in the units of bars. Note that 1 bar is equivalent to 14.5 pounds per square inch, and in the case of soils is the suction exerted by plants or a negative pressure. Field capacity is the amount of water in a soil (or material tested) after the soil/material has been wetted to saturation and allowed to drain by gravity. Field capacity is equivalent to -0.33 bars of matric suction when applied in a pressure plate apparatus in the lab. When considering soils, sandy soils have lower water holding capacity than clay soils. Products that hold generous amounts of water are less subject to losses of nutrients by leaching. Products with a lower water holding capacity (i.e. wool products) reach the saturation point sooner than a product with a higher water holding capacity (i.e. straw ECB, compost). After a product is saturated, all of the excess water and some of the nutrients are leached into in the soil profile.

The WHC and saturation results indicate wool products hold more water and make the water more readily available to the soil environment (Table 17). Wilting point is defined as negative 15 bars of matric suction. Anomalous results were observed for the wilting point results and are not reported in the table. The WHC measurement is best suited to soil, so some caution is urged in interpreting the exact values reported for the erosion control materials. However, it is clear that all of the ECB materials hold appreciable amounts of water.

4.4 Conclusions

The woolen reclamation products test results - mass per unit area assessment, standardized ECB laboratory tests and nutritional and water holding capacity tests - provided valuable information on the wool products, their future development, and their deployment on roadside reclamation projects.

Silt Fence

The heavier weight wool silt fence (244 g/m^2) was highly variable in mass per unit area, where as the lighter weight silt fence (140 g/m^2) and wool/burlap silt fence had a more even distribution of mass per unit area. If pursued in future development, the heavier weight wool silt fence should focus on a more even distribution of fibers to improve its strengths and eliminate weaker areas in the fence.

ECBs

The woolen ECB products exhibited variability in mass per unit area due to the uneven distribution of their straw, and/or wool fill components that are placed between two layers of sisal netting. However, the standard straw/coconut ECB also had variability in its weight indicating that an even distribution of fill components may not be standard for rolled ECBs. If it is deemed important, future manufacturing improvements could standardize production of the new wool-straw ECB products for more uniform results.

There was some inconsistency with mass per unit area of the wool/straw ECB. It may be worth re-testing three replications of the wool/straw ECB after manufacturing is fine-tuned and can produce a more even distribution of the wool/straw filler layer within the rolled ECB.

The laboratory tests for tensile strength, C-factor and shear stress gave some indication of the wool/straw ECB's performance. These results should be viewed with some caution since only one replication of each test was performed due to the costs of such testing. Normally, transportation agencies would require 3 replications of each test. The wool ECB:

- met MDT tensile strength standards for a short term (Type II B, C) or long term (Type III A) ECB,
- exceeded the minimum shear stress specified in the MDT standard specifications for short term ECB (Type II B) for low level events, but not for high level events, and was lower than the updated minimum shear stress level for short term ECB,
- the C-factor was representative of a short-term ECB (Type II C).

In general, the wool/straw ECB was comparable to a short-term (Type II B or C) standard ECB commercially produced and used along MDT and other transportation agency roadways. Future product development of the wool/straw ECB should focus on improving the shear strength at high flows so it meets all required Type III specifications. This most likely can be achieved by evaluating stronger mesh netting that the wool-straw filler is sandwiched between.

The analytical laboratory tests showed that the wool-straw ECB has three features that may it improve roadside plant establishment and growth and reduce erosion:

- It has higher nitrogen levels than the standard materials (straw ECB or compost) which may provide a benefit to the establishment and growth of new vegetation over the long term as the wool decomposes.
- The wool ECB products have a high percent saturation value.

Wool as an Additive to Compost

Due to the total nitrogen level in wool and its water holding capacity and its fibrous nature, cut wool pieces as an additive to compost may serve to help compost blankets perform better over the long term. There was a limited amount of experimentation available in this project to explore this potential, only one ratio of wool to compost was recommended for field tests. Further research will be necessary to more fully understand the ideal mix of wool as an additive to compost and to explore the different types of commercial composts that MDT and other transportation agencies currently use.

5 FIELD TESTS

An important component of evaluating the effectiveness of promising woolen roadside reclamation products was to test them along Montana highways. Field tests of the woolen products evaluated their effectiveness compared to standard practices or to other controls. For wool as an additive to compost or as a component of erosions control blankets, the control was to not deploy them at all.

The primary objective of field tests was to evaluate woolen product performance for plant establishment in comparison to existing standard materials via field experiments. Three woolen reclamation products were selected as promising products for testing were:

- Wool silt fence
- Wool erosion control blankets (ECBs) of varying densities, thicknesses and strength
- Wool as an additive to conventional wood-based compost

The objectives for the three categories of wool reclamation products were to:

- Compare the effectiveness of different weights and types of wool erosion control blankets (ECBs) developed by the project to traditional straw / coconut ECB, and
- Determine whether each of the wool ECBs resulted in greater vegetative establishment than straw/coconut ECB. Determine if 1.9 centimeter (cm) (0.75 inch (in)) cut wool incorporated into wood-based compost outperforms the compost alone.

5.1 Materials and Methods

The research consisted of a series of field tests for newly developed woolen reclamation products produced in cooperation with Montana wool producers and a Minnesota ECB manufacturer. Products were tested at active highway revegetation projects selected by the MDT Reclamation Specialist along U.S. Highway 287 near Three Forks, MT, U.S. Highway 12 near Martinsdale, MT, and at WTI's Transcend test facility near Lewistown, Montana, where a constructed test slope (3H:1V) is used for experiments (Figure 14). Three categories of wool reclamation products were developed by the project: 1) silt fence, 2) ECBs and 3) cut wool used as an additive to wood-based compost. They were evaluated at various field sites in Montana during 2015 and 2016. The project sought to evaluate the effectiveness of the wool products and compare them to traditional commercial products currently used by MDT and other state transportation agencies.

There were no known wool silt fence products available anywhere in the world for the project to test. Thus, the first step for silt fence was developmental. Project team members worked with three different wool mills in Montana to better understand how to manufacture wool silt fence. Thus, the development of wool silt fence took a heuristic approach for development and field testing. Ultimately, three different versions of wool silt fence were developed and tested in the field over the two years of the project (see Sections 5.3 and 5.4). The first version was developed by a Montanan wool mill using wool batts that were stitched together to make a roll of material. The second version was developed by the same wool mill and a canvas shop. The canvas shop had industrial sewing machines with stitching capabilities to sew the wool batts together and add horizontal and/or vertical stitching to strengthen the material. The last version was made with an ECB manufacturer in Minnesota using cut wool pieces placed between two layers of burlap and stitched together. Due to the putative nature of the wool silt fence products developed for the project, data collected to evaluate their functionality was ocular and photographic (observational).

To evaluate the effectiveness of the wool ECBs, the site preparation, seed mix and seed rate were held constant for each of the ECB field locations. Controlling these site variables allowed for a single dependent variable to be measured to assess the efficacy of each wool treatment. Vegetative canopy cover was the sole dependent variable measured during monitoring. Vegetative canopy cover was recorded for each species in each experimental plot so that seeded, non-seeded and weedy species relative abundance could be measured and evaluated statistically. Treatments were replicated eleven times at the Highway 287 research site and ten times at the Transcend site to facilitate statistical inference.

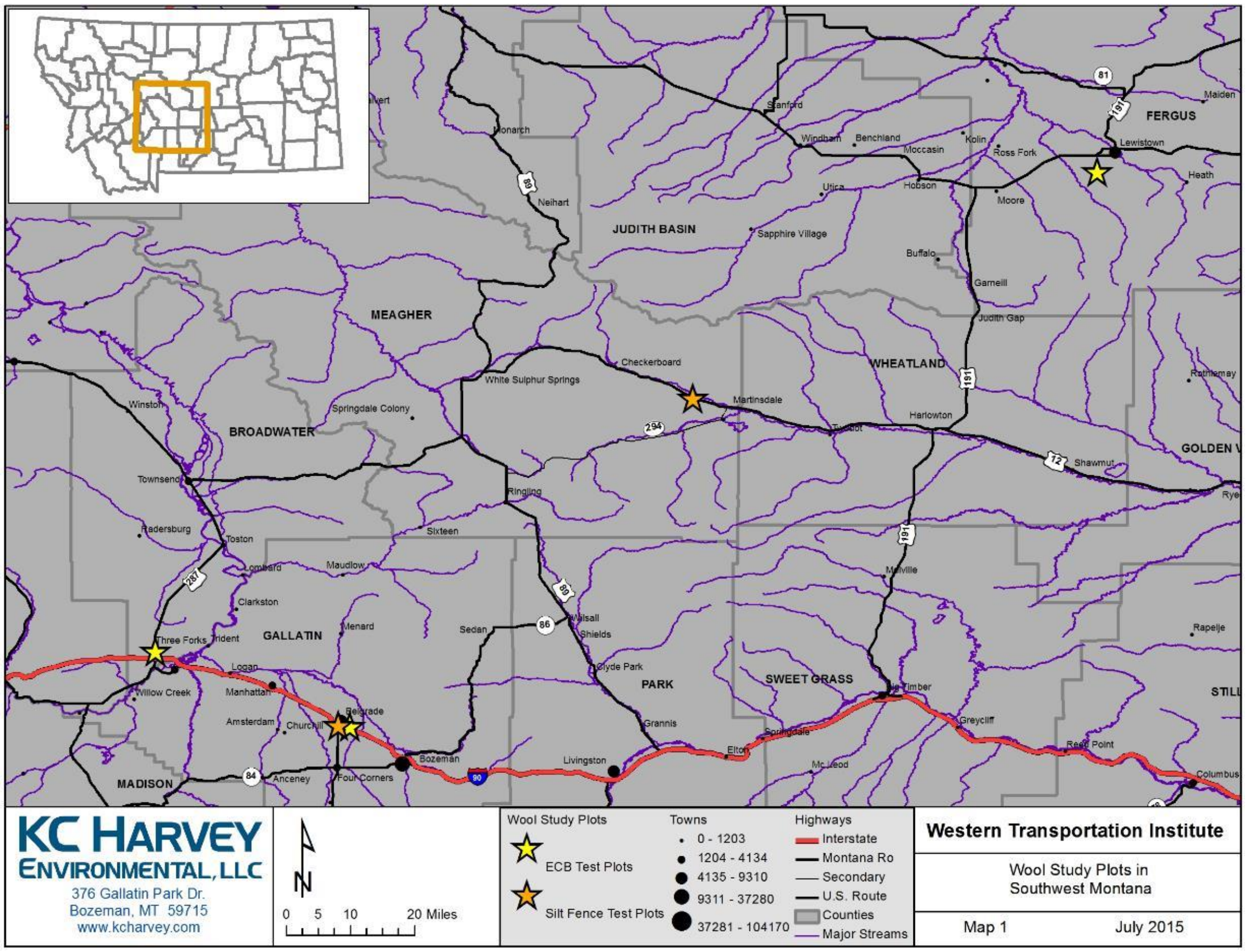


Figure 14: Field test site locations in Montana.

The wool-compost blended product was evaluated similarly to the ECBs. It was compared to a wood-based compost control treatment developed from typical compost prescriptions used regularly by MDT on its post-construction roadside reclamation projects. Site preparation, seed mix and seed rate were identical for both the traditional compost and the compost with wool pieces added. The plant canopy cover was recorded for each species for each experimental plot.

5.1.1 Silt Fence

Three different generations of wool silt fence were developed and successively installed on the Checkerboard Martinsdale-East highway project, formally described by MDT as STPP-HSIP 14-2(29)72. The reconstruction project was located on Highway 12 between MP 71 and MP 77. The road surface was widened and straightened to current highway design standards. During reconstruction, topsoil was salvaged, stockpiled and then reapplied at a 2 – 8 cm (1 – 3 in) depth. Roadsides were disked and harrowed, and then all slopes angles 3:1 or less were drill seeded. At the time of initial wool silt fence installation in 2014, the area had been drill seeded; however little to no germination had occurred.

There were four field tests of the first generation of silt fence, which consisted of 100% biodegradable 244 g/m^2 (7 oz/yd^2) wet felted wool batts. The silt fence was manufactured by Sugar Loaf Wool Carding Mill. Each rectangular wool batt was approximately 106.7 cm (42 in) by 91.4 cm (36 in), and was subsequently sewed together by Custom Canvas Design of Bozeman, MT into a continuous roll of wool silt fence 106.7 cm (42 in) wide. The silt fence was installed at the field site on August 28, 2014 (Table 18). The four locations were selected because erosion was visually observed indicating it would provide adequate conditions to test the product's ability to capture sediment, withstand surface runoff volumes typical of MDT roadsides, and endure through the winter and spring conditions. All wool silt fence was installed consistent to standard geotextile silt fence fabric and similar to MDT specifications (see drawing 208-30, Supplemental to the MDT Standard Specifications for Road and Bridge Construction, 2016). A six inch, v-shaped ditch was dug to bury and backfill the bottom six inches of the wool fabric. The above-ground portion of wool silt fence was stapled to 1.2 m (4 ft) tall wood stakes placed at approximately 1 m (3 ft) spacing for support (Figure 15a). The first generation of silt fence was monitored in October 2014 and January 2015.

The second generation of silt fence included stitching to increase strength and longevity of the product. Custom Canvas Design of Bozeman, MT stitched at 10 cm (4 in) intervals into two layers of 140 g/m^2 (4 oz/yd^2) felted wool silt fence (Figure 15b). A plastic mesh net was stitched between the two layers of felted wool to increase strength of the resultant fence. Two second generation silt fences and one plastic geo-textile silt fence (control) were installed in July 2015 at locations 2, 3, and 1, respectively (Table 18). The second generation of silt fence was monitored in October 2015 and June 2016.

Table 18: Wool silt fence field locations installed August 28, 2014.

Location	Nearest Town	Latitude	Longitude
1	Martinsdale, MT	46°30'31.5144 N	110°23'09.7926 W
2	Martinsdale, MT	46°30'30.9646 N	110°23'10.7120 W
3	Martinsdale, MT	46°30'27.3790 N	110°23'01.6508 W
4	Martinsdale, MT	46°30'22.6742 N	110°22'46.6626 W

In February, a project researcher visited Ero-Guard in Mapleton, Minnesota, to observe their ECB manufacturing facility and discuss techniques to improve upon the current wool products. A third generation 100% biodegradable silt fence was designed that consisted of two burlap sheets stitched together with a shredded wool center sandwich. The third generation of wool/burlap silt fence was much easier and less costly to produce at larger scales than the previous generation felted wool silt fence. This final version of silt fence for this project could also potentially be used in automated silt fence installation machinery currently used for woven plastic silt fence (standard fence used as a control) installation. The third version of silt fence, made of wool and burlap, was installed at locations 2 and 3 in June 2016 (Figure 15c) and was monitored in July 2016.

(a) First generation silt fence – pure wool, wet felted, batts stitched together in a continuous roll. August 2014.

(b) Second generation silt fence - 2 pure wool, wet felted layers from batts, plastic mesh in between the wool layers, and extra horizontal stitching. July 2015.

(c) Third generation silt fence-2 layers of burlap, with shredded wool in center, stitched together in continuous roll. June 2016.

(d) Woven plastic silt fence (control). July 2015.

Figure 15: Three generations of wool silt fence and standard woven plastic silt fence tested in field trials, 2014 – 2016.

5.1.2 Wool Erosion Control Blankets and Compost on Highway 287

As an outcome of materials selection, a variety of the most promising woolen materials were selected for field tests (Table 19). A field site on a roadside cut slope along U.S. Highway 287 (45°56’12.5959 N; 111°35’48.9750 W) near Three Forks, MT, was selected for the wool ECB and wool compost field test site (Figure 14). This site was selected because it was a recently constructed highway project that failed to successfully revegetate after drill seeding in 2003 after construction. The slope is west facing and approximately 2H:1V slope.

Table 19: Treatments tested in experimental plots along U.S. Highway 287, Three Forks, MT.

Treatment Number	Descriptions of Experimental and Control Treatments	Product Developer
1	Carded Wool Blanket (73 g/m^2; 2 oz/yd^2)	Thirteen Mile Lamb and Wool Company
2	Carded Wool Blanket (44 g/m^2; 1 oz/yd^2)	Thirteen Mile Lamb and Wool Company
3	Needle punched (one pass) felted wool blanket	Brookside Woolen Mill
4	Needle punched (four pass) felted wool blanket	Brookside Woolen Mill
5	Compost with cut wool; 40:1	Mix of Mountain West Product's Glacier Gold + Brookside Woolen Mill cut wool
6	Control: standard 70% straw / 30% coconut ECB	Ero-Guard, Inc.
7	Control: Compost	Mountain West Products' Glacier Gold
8	Control: Broadcast seed only	N/A
9	Control: no seed or treatments	N/A
10	100% wool ECB	Ero-Guard, Inc.
11	50% wool / 50% straw ECB	Ero-Guard, Inc.

Eleven treatments were field tested at the U.S. Highway 287 field site including carded wool blankets, needle punched wool blankets, wool/straw ECBs, cut wool with compost, and controls. Prior to plot establishment, the site was sprayed with glyphosate (Roundup®) to remove all existing vegetation (sparse seeded and non-seeded plants) and raked to improve seed-to-soil contact.

Treatments, except for treatments 10 and 11 (Table 19), were arranged in a randomized complete block design with eleven replications of each treatment (

Table 20; Figure 16). The eleven replications of treatments 10 and 11 were added to the north end of the field site because the material arrived at a later date and was not part of the original experimental design. The treatment installation dates varied due to delays in product manufacturing and shipping. Treatments 1, 2, 5, 6, 7, 8 and 9 were installed October 17, 2014. Treatment 3 was installed on November 5, 2014, and treatments 4, 10 and 11 were installed on May 7, 2015.

Treatment plots were 1 m^2 (10.2 ft^2) with 0.5 m (1.6 ft) spacing between plots. Each treatment plot was held in place using a 1 x 1 cm (0.4 in) gauge biodegradable coconut netting and secured with steel sod staples. Seeding took place at the time of treatment installation using a standard MDT seed mix (Table 4). Glacier Gold® compost was used and the compost with wool was weighed and mixed by the research team. The compost and compost with wool was applied at a 1.3 cm (½ in) depth as recommended by a previous MDT research project (Ament et al. 2011).

Vegetative canopy cover, defined as the vertical projection of the crown or shoot area of a species projected on the ground as a percent of the reference area (Mueller-Dombois and Ellenburg 1974), was recorded by species in September 2015 and July 2016. Photographs of the field site and treatment plots were taken during each field event. In addition, one composite soil sample was collected to analyze baseline nutrient content of the Highway 287 field site. Soil erosion was not measured at Highway 287 site because the treatments did not cover the entire length of the slope; therefore, erosion may have been influenced by other up-slope conditions and gaps between plots.

Table 20: Randomized block design of eleven treatments replicated eleven times at U.S. Highway 287 field site.

Slope Top													
11	11	10	2	6	5	5	8	2	9	7	3	4	8
11	11	10	4	3	7	7	1	3	6	3	6	5	6
10	11	10	7	5	1	9	7	8	1	1	1	1	2
10	11	10	9	9	4	8	4	4	7	5	8	7	1
	11	10	6	8	3	1	6	1	5	8	7	6	9
	11	10	8	4	9	4	3	6	8	9	9	2	5
	11	10	3	7	8	6	9	9	4	6	4	8	3
	11	10	1	2	6	3	5	7	2	2	5	9	4
	11	10	5	1	2	2	2	5	3	4	2	3	7
All replications for Treatments 10 & 11			**Rep 1**	**Rep 2**	**Rep 3**	**Rep 4**	**Rep 5**	**Rep 6**	**Rep 7**	**Rep 8**	**Rep 9**	**Rep 10**	**Rep 11**
U.S. Highway 287 ROW													

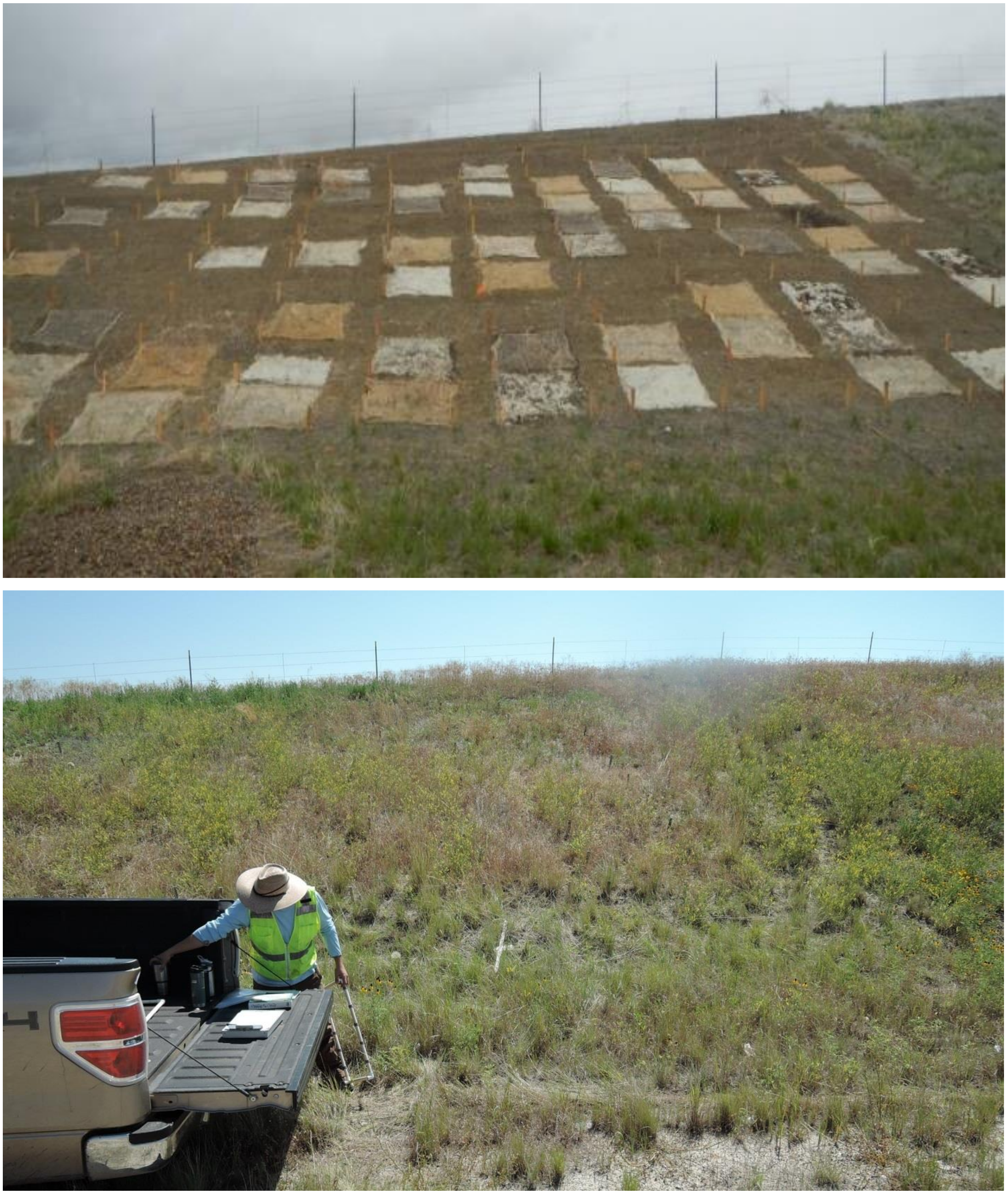


Figure 16: Above: Experimental layout of 9 treatments with eleven replications at the Highway 287 field site, October 2014 (wool/straw ECB treatments installed in 2015 not pictured). Below: Vegetation that developed in the 11 treatments by July 2017.

Species were grouped as seeded native grasses, desired non-seeded grasses and forbs (including the 2003 seeded species), and weeds for statistical analysis. Seeded grasses consisted of the four native species seeded for this experiment (Table 21). The desired non-seeded grasses and forbs group consisted primarily of species that may have been previously present on the site and re-established, or species that colonized the site which provide cover and soil stability. Desired non-seeded species primarily consisted of western wheatgrass (*Pascopyrum smithii*), green needlegrass (*Nassella viridula*), and yellow sweetclover (*Melilotus officinalis*). The weeds were primarily kochia (*Kochia scoparia*), tumble mustard (*Sisymbrium altissimum*), annual brome grasses (*Bromus* spp.), and Russian thistle (*Salsola tragus*).

To determine effects of woolen and control ECB treatments on plant canopy cover, we conducted pairwise t-tests between the respective means, separately for each plant group. We applied Bonferroni corrections to account for multiple testing (Miller 1981). Plant canopy cover values were arcsine-transformed prior to analysis to meet t-test assumptions such as normality of data distribution, adequacy of sample size, and equality of variance in standard deviation. To determine if wool added to compost affected plant canopy cover, we conducted t-tests between the compost with wool and compost alone (control) treatment for each of the three plant groups. Plant canopy cover values were arcsine-transformed prior to analysis to meet t-test assumptions. Nontransformed means are presented for ease of data interpretation.

5.1.3 Wool Erosion Control Blankets at Transcend

A constructed test slope as WTI's Transcend test facility located near Lewistown, MT (Lat. 47°01'48.19" N, Long. 109°28'15.75" W) was used as a second field test site for evaluating the wool / straw ECBs and the straw / coconut ECB as the control (Figure 17). The test slope at Transcend is a 2H:1V (2 horizontal:1 vertical) slope and is comprised of local subsoil. The slope dimensions are 100 m (328 ft) long and 5 m (16.4 ft) high. Soils were tested for nutrient content after construction of the test slope in 2013 and again during the second growing season in 2017.

Figure 17: Test slope (2H:1V) constructed at Transcend, a WTI-MSU experimental station in Lewistown, MT.

Prior to plot establishment, the entire slope was sprayed twice (May and early June 2015) with a 6% glyphosate (Roundup®) solution to remove all existing vegetation. The test site was then hand-weeded and raked prior to seeding and installing the ECBs. On June 23 and 24, 2015, the slope was seeded using the standard MDT seed mix (Table 4) and six ECB treatments were installed on the test slope (Table 21 and Figure 17). Treatments were arranged in a randomized block design with ten replications. Each treatment plot was 1.5 m wide by 5 m long to cover the height of the slope (Figure 18). Treatment plots were placed on the south facing slope (azimuth 180 degrees).

Table 21: The six ECB treatments tested at the Transcend field site.

Number	Treatment[1]
1	Control A: No ECB
2	Control B: Standard 70% Straw / 30% Coconut ECB
3	100% Wool ECB
4	40% Wool / 60% Straw ECB
5	25% Wool / 75% Straw ECB
6	55% Wool / 45% Straw ECB

[1] The control and wool/straw ECBs were produced by Ero-Guard Inc.

Figure 18: One replication of the six treatments at the Transcend test slope.

Vegetative canopy cover was recorded by species in October 2015, July 2016, and June 2017 at the Transcend field site. Photographs of the field site and treatment plots were taken during construction and each sampling event.

Species were grouped as seeded native grasses, desired non-seeded grasses and forbs, and weeds for statistical analysis. Seeded grasses consisted of the four native species seeded for this experiment. The desired non-seeded grasses and forbs group consisted primarily of species that naturally colonized the site from the surround area and provide cover and soil stability. Desired non-seeded species primarily consisted of smooth brome (*Bromus inermis*), witchgrass (*Panicum capillare*), and white sweetclover (*Melilotus alba*). The weed species were primarily field bindweed (*Convolvulus arvenis*), kochia (*Kochia scoparia*), prickly lettuce (*Lactuca serriola*), annual brome grasses (*Bromus* spp.), and alyssum (*Alyssum desertorum*).

To determine the effects of wool and control ECB treatments on plant canopy cover, we conducted pairwise t-tests between the respective means, separately for each plant group. We applied Bonferroni corrections to account for multiple testing (Miller 1981). Plant canopy cover values were arcsine-transformed prior to analysis to meet t-test assumptions such as normality of data distribution, adequacy of sample size, and equality of variance in standard deviation. Non-transformed means are presented for ease of data interpretation.

5.2 Results

5.2.1 Silt Fence

The October 2014 observation of first generation silt fence found that it was able to capture sediment and filter water (Figure 19a). However, all four locations of the first version of wool silt fence were beginning to lose form – sagging, small holes – probably due to wetting events. This was a pure wool fence which was felted, thus had no additional strengthening materials. It appeared that it would not be able to survive intact, and fully functional, for two years. It indicated that future wool silt fence products needed additional inputs – stitching, mesh, etc. – to increase tensile strength and longevity. The first version of silt fence was removed in June 2015.

(a) First generation silt fence, October 2014.

(b) Second generation silt fence, June 2016.

(c) Third generation silt fence, July 2016.

(d) Third generation (foreground) and second generation (background) silt fence, July 2016.

Figure 19: Photo monitoring the three generations of wool silt fence developed and tested in field trials along U.S. Highway 12, 2014 – 2016.

The second version of the silt fence maintained its form one year after installation (Figure 19b). The additional stitching and mesh netting reinforcement strengthened the wool silt fence and extended its functional life. After enduring several summer thunderstorm events in 2015, there was visual evidence it was fully successful in filtering water and containing sediment. However, parts of the second generation of the silt fence were beginning to biodegrade one year after installation, exposing mesh netting or creating small holes in the fabric, indicating that it could function as a short-term roadside reclamation product. This version of wool silt fence lacked the durability needed for multi-year roadside projects.

The two locations where the third generation of the silt fence was installed were monitored one month after installment. These burlap and wool silt fences were found lying on the ground with signs of a heavy rain and storm event that covered the fence with sediment and debris (Figure 19c and Figure 19d). While the third generation of the silt fence did not withstand the storm event, the two remaining second generation silt fences remained in place and were functioning. It appears two layers of burlap and a layer of wool may be too restrictive to water flow during storm events. It appears that this product, although easily produced with existing ECB manufacturing equipment, will need further development that adjusts the amounts of burlap and wool content.

5.2.2 Wool Erosion Control Blankets and Compost on Highway 287

Soil nutrient content for the Highway 287 field site prior to, and after, treatment installation is presented in Table 22. Soil pH, electrical conductivity (EC), sodium adsorption ratio (SAR), and organic matter (OM) were within recommended ranges for establishing native grasses (Table 22). Potassium (K) levels were over twenty times the recommended ranges. Phosphorous (P) and the form of nitrogen available for plant growth (NO_3) were below recommended nutrient ranges for establishing native grasses (Table 22). Thus, the Highway 287 site is nutrient poor for the two important macronutrients for plant establishment and growth. However, selecting a harsh site (i.e. nutrient poor, arid) was an objective of the study design was to determine if wool products can improve plant establishment in challenging conditions.

The initial soil sample composite was collected in 2014 from the entire site prior to plot installation and is reported as the 'pre-treatment' soil characteristics. After 2015 plot construction using 11 replications of 11 treatments the soil characteristics of 6 selected treatments were sampled in 2017 including: control (no seed/no erosion control), seed only, compost+seed, straw/coir ECB+seed, 50% wool+seed and 100% wool+seed. Each treatment type was sampled by compositing soil from each of the 11 replications. Results from 2017 soil sampling are comparatively uninteresting in comparing the pre-treatment and post-treatment characteristics. Soil pH remained relatively constant and varied between 7.4 and 7.8. Soil electrical conductivity dropped appreciably between 2014 and 2017 resulting in decreased SAR, water soluble Ca, Mg, Na, NO_3, and K. Soil P remained approximately the same while OM decreased from 2.8% to ~1.0% with the exception of the compost plot which increased to 3%.

Importantly the total soil nitrogen levels increased from 0.3% to a mean of 0.87% in the wool plots, 1.34% in the compost plot and 0.79% in the straw/soir ECB plot. The reason for decreased OM levels after treatment is unexplained, possibly due to the mineral soil sampling occurring underneath the ECB rather than including the fabric in the soil sample. The reductions in EC and water soluble constituents may be due to the occurrence of a 2 inch rain storm in the weeks prior to sampling. However, the increase in total nitrogen in the mineral soil is encouraging and suggests that degradation of the soil surface erosion control treatments is resulting in material degradation and leaching of nutrients into the underlying mineral soil. Plant measurements suggest the beneficial responses observed from improved soil nutrient status. This finding mirrors the observation of Polish researchers evaluating the rapid breakdown of wool textiles developed for erosion control and revegetation (Broda et al. 2016).

Table 22: Soil chemical characteristics before and after treatment, U.S. Highway 287 site.

Analysis[1]	Values for Pre-Treatment and Treatment Type[2] Soils (Year Sampled)						
	Pretreatment[3] (2014)	Treatment 6 (2017)	Treatment 7 (2017)	Treatment 8 (2017)	Treatment 9 (2017)	Treatment 10 (2017)	Treatment 11 (2017)
pH	7.7	7.8	7.4	7.8	7.8	7.6	7.5
EC (dS/m)	3.1	0.6	0.6	0.5	0.8	0.8	0.5
SAR (unitless)	5.8	2.9	3.3	3.4	3.7	3.1	2.9
Ca (mg/L)	379	52	47	30	71	68	44
Mg (mg/L)	29	6.1	6.4	4.4	6.9	6.3	4.5
Na (mg/L)	434	83	91	74	121	99	75
OC (%)	1.6	0.6	1.8	0.7	0.7	0.7	0.6
OM (%)	2.8	1.0	3.1	1.2	1.2	1.1	1.0
K (mg/kg)	2,770	513	534	466	488	435	457
P (mg/kg)	3.0	3	19	4	4	2	2
NO_3, (mg/kg)	8.0	<1	<1	<1	<1	3	3
N-Total (%)	0.3	0.79	1.34	0.79	0.45	0.96	0.79

[1] Analysis: EC = electrical conductivity; SAR = sodium adsorption ratio; Ca = calcium; Mg = magnesium; Na = sodium; OC = organic carbon; OM = organic matter; K = potassium; P = phosphorous; NO_3 = Nitrate; N = nitrogen; C:N = carbon to nitrogen ratio; dS/m=deciSiemen per meter; mg/L = milligrams/liter; mg/kg = milligrams/kilogram.
[2]Recommended range from Colorado State University Soil Testing Laboratory.
[2] Treatment Type: Treatment 6= Standard 70%Straw/30%Coir ECB; Treatment 7=Compost (control); Treatment 8=Broadcast seed only (control); Treatment 9=no seed (control; Treatment 10=100% wool ECB; Treatment 11= 50% wool/50% straw ECB. Soil samples were collected from all 11 replications of each treatment and collectively placed in a single bag, a sample was then drawn from the bag and this composite was sent to a commercial lab for analysis.
[3] Pretreatment soil samples were collected from 10 random locations on the US 287 test slope before experimentation, they were collectively placed in a single bag, a sample was then drawn from the bag and this composite was sent to a commercial lab for analysis.

Table 23: Mean percent canopy cover of plant groups by treatments at Highway 287 test site.

Treatment	Description	Mean Percent Canopy Cover (%)		
		Seeded Native Grass	Desired Non-Seeded Species	Weed Species
1	Carded Wool Blanket (73 g/m²; 2 oz/yd²)	8.6	3.2	17.8
2	Carded Wool Blanket (44 g/m²; 1 oz/yd²)	9.7	4.5	21.5
3	Needle punched (one pass) felted wool blanket[2]	15.1	3.2	20.4
4	Needle punched (four pass) felted wool blanket	2.9	2.0	24.3
5	Compost with cut wool; 40:1	10.2	1.7	39.1
6	Control: standard 70% straw / 30% coconut ECB	4.7	5.0	17.7
7	Control: Compost	6.4	1.3	35.4
8	Control: Broadcast seed only	0.9	2.9	47.1
9	Control: no seed or treatments	0.9	3.5	49.8
10	100% wool ECB	20.9	1.4	10.8
11	50% wool / 50% straw ECB	24.6	2.1	13.6

[1] Treatment 1&2: Thirteen Mile Lamb and Wool Company; Treatment 3&4: Brookside Woolen Mill; Treatment 5: Mountain West Product's Glacier Gold + Brookside Woolen Mill cut wool; Treatment 6,11,&12: Ero-Guard, Inc.; Treatment 7: Mountain West Product's Glacier Gold

[2]Treatment is missing two replications due to lack of material.

There were no significant differences between treatment effects on mean plant canopy cover in 2015. In 2016 significant differences were observed reflecting differences in mean canopy cover by the different plant groups after two growing seasons (Table 23). Pairwise t-tests were used to determine whether the mean canopy cover of each treatment, for each plant group, were statistically different from one another. That is, the t-tests compared one treatment to one other treatment with all combinations of treatments assessed (see Table 24 and Table 25). P-values that are less than 0.05 are used to determine when the treatments differ, that the difference is not due to random chance but can be attributed to the treatment (P-values > 0.05 indicate that the differences in the two treatments being compared are likely to occur by random chance). Tables 24 and 25 provide P-values for significant differences in seeded species and weed species canopy cover for ECB products. No table was created for the P-values for compost versus compost with cut wool treatments, instead the P-values are in the text.

Seeded grass establishment ranged from 0.9% to 24.6% canopy cover after two growing seasons with the broadcast seed and no seed controls having the lowest seeded species establishment and the 50% wool / 50% straw ECB having the highest percent cover (Table 23). In general, the three controls had significantly lower seeded grass canopy cover than all the wool treatments except the four-pass needle punch blanket (Table 23). T-test comparisons of wool ECBs found the 100% wool and 50% wool / 50% straw treatments to have significantly greater seeded grass cover than both carded wool blankets and four pass needle punch blanket treatments. The compost with cut wool did not have significantly greater seeded grass cover than compost alone (P = 0.137).

The amount of **desired non-seeded species** that re-established on the treatment plots was low, ranging from 1.3 – 5.0 percent canopy cover. The canopy cover of desired non-seeded species did not significantly differ for any ECB treatment (P = 1.0 for all t-tests). In addition, desired non-seeded species canopy cover did not differ on the compost with wool compared to the compost control (P = 0.504). Therefore, species re-establishing or colonizing the site which provide canopy cover and soil stability were relatively evenly distributed on the study site.

Weed species established on the treatment plots at mean canopy covers of 10.8% to 49.8% (Table 23). Weed canopy cover was greater than seeded species canopy cover in all treatments except the 100% wool and 50% wool / 50% straw ECB treatments which had greater canopy cover of seeded grasses. Wool treatments did not differ significantly in the weed canopy cover (P = 1.0 for all t-tests). The only significant differences in the amount of weed cover was in comparison to the control. The straw / coconut control had significantly less weed cover (17.7%) than the seed only (47.1%; P = 0.019) and no seeding (49.8%; P = 0.007) controls. The seed only control also had significantly greater weed cover than the 73 g/m^2 carded wool blanket, 100% wool ECB, and 50% wool / 50% straw ECB treatments (Table 24). Similarly, the no seeding control had significantly greater weed cover than all treatments except the four-pass needle punch treatment. The compost with cut wool did not have significantly greater weed canopy cover than compost alone (P = 0.635).

Table 24: P-values generated from independent t-tests of mean seeded species canopy cover between ECB treatments. Significant values (< 0.05) highlighted for interpretation. See Table 24 for mean values.

TREATMENTS[1]	T 6: Control: 70% straw/ 30% coconut	T 8: Control: Seed only	T 9: Control: No seeding	T 1: Carded Wool (73 g/m²)	T 2: Carded Wool (44 g/m²)	T 3: Needle punch (1 pass)	T 4: Needle punch (4 pass)	T 10: 100% wool	T 11: 50% wool / 50% straw
T 6: Control: 70% straw / 30% coconut	-	-	-	-	-	-	-	-	-
T 8: Control: Seed only	0.079	-	-	-	-	-	-	-	-
T 9: Control: No seeding	0.050	1.000	-	-	-	-	-	-	-
T 1: Carded Wool (73 g/m²)	1.000	0.000	0.000	-	-	-	-	-	-
T 2: Carded Wool (44 g/m²)	1.000	0.000	0.000	1.000	-	-	-	-	-
T 3: Needle punch (1 pass)	0.002	0.000	0.000	0.663	1.000	-	-	-	-
T 4: Needle punch (4 pass)	1.000	1.000	1.000	0.058	0.031	0.000	-	-	-
T 10: 100% wool	0.000	0.000	0.000	0.001	0.002	1.000	0.000	-	-
T 11: 50% wool / 50% straw	0.000	0.000	0.000	0.000	0.000	0.244	0.000	1.000	-

[1] Manufacturers: Treatment 1&2: Thirteen Mile Lamb and Wool Company; Treatment 3&4: Brookside Woolen Mill; Treatment 6, 10 &11 Ero-Guard, Inc.

Table 25: P-values generated from independent t-tests of mean weed species canopy cover between ECB treatments. Significant values (< 0.05) highlighted for interpretation. See Table 24 for mean values.

TREATMENTS[1]	T 6: Control: 70% straw/ 30% coconut	T 8: Control: Seed only	T 9: Control: No seeding	T 1: Carded Wool (73 g/m^2)	T 2: Carded Wool (44 g/m^2)	T 3: Needle punch (1 pass)	T 4: Needle punch (4 pass)	T 10: 100% wool	T 11: 50% wool / 50% straw
T 6: Control: 70% straw / 30% coconut	-	-	-	-	-	-	-	-	-
T 8: Control: Seed only	0.019	-	-	-	-	-	-	-	-
T 9: Control: No seeding	0.007	1.000	-	-	-	-	-	-	-
T 1: Carded Wool (73 g/m^2)	1.000	0.025	0.010	-	-	-	-	-	-
T 2: Carded Wool (44 g/m^2)	1.000	0.061	0.024	1.000	-	-	-	-	-
T 3: Needle punch (1 pass)	1.000	0.061	0.026	1.000	1.000	-	-	-	-
T 4: Needle punch (4 pass)	1.000	0.404	0.183	1.000	1.000	1.000	-	-	-
T 10: 100% wool	1.000	0.000	0.000	1.000	1.000	1.000	1.000	-	-
T 11: 50% wool / 50% straw	1.000	0.001	0.000	1.000	1.000	1.000	1.000	1.000	-

[1] Manufacturers: Treatment 1&2: Thirteen Mile Lamb and Wool Company; Treatment 3&4: Brookside Woolen Mill; Treatment 6, 10 &11 Ero-Guard, Inc.

5.2.3 Wool Erosion Control Blankets at Transcend

At the time of pre-treatment soil sampling after the construction of the Transcend test slope in 2012, it was a berm of fill material and lacked both top soil and stabilizing vegetation. Soil OM and nutrient levels were modest in 2012 as were pH, EC, Ca, Mg, Na, and SAR suggesting some potential for plant growth (Table 26). The intent of this research site was to construct a fill slope out of low quality soil materials that were inhospitable to plant growth. Subsequent to construction of the research slope the wool ECB treatments were applied. Final monitoring of soil quality and vegetation condition occurred in 2017. Similar to the Highway 287 soil test results, the soil pH remained nearly constant and soil electrical conductivity (EC) decreased by approximately one-half across all treatments compared to the pretreatment values (Table 26). The reduced soil EC was accompanied by similar reductions in Ca, Mg, Na and SAR as measures of the bulk soil soluble constituents. Soil OM and NPK fertility likewise remained in a narrow range between 2012 and 2017. No major geochemical changes to the soil resulted from the erosion control blanket installation (Table 26).

Table 26: Soil chemical characteristics before and after treatment, Transcend test slope, Lewistown, MT.

Analysis[1]	Values for Pre-Treatment and Treatment Type[2] Soils (Year Sampled)						
	Pretreatment[3] (2012)	Treatment 1 (2017)	Treatment 2 (2017)	Treatment 3 (2017)	Treatment 4 (2017)	Treatment 5 (2017)	Treatment 6 (2017)
pH	7.9	7.9	7.9	8.0	7.9	7.9	7.8
EC (dS/m)	0.7	0.3	0.2	0.3	0.3	0.3	0.3
SAR (unitless)	0.49	0.2	0.2	0.2	0.1	<0.1	0.1
Ca (mg/L)	69	38	35	39	42	37	40
Mg (mg/L)	29	12	11	13	13	12	12
Na (mg/L)	19	4.4	3.9	5.5	2.8	2.5	3.7
OC (%)	1	0.8	0.8	0.7	0.9	0.8	0.8
OM (%)	1.7	1.3	1.4	1.3	1.5	1.4	1.3
K (mg/kg)	150	157	179	175	193	152	147
P (mg/kg)	7	5	4	4	4	5	4
NO_3, (mg/kg)	4	1	<1	4	3	1	4
N-Total (%)	-	095	0.95	0.90	0.96	0.95	0.96

[1]Analysis: EC = electrical conductivity; SAR = sodium adsorption ratio; Ca = calcium; Mg = magnesium; Na = sodium; OC = organic carbon; OM = organic matter; K = potassium; P = phosphorous; NO_3 = Nitrate; N = nitrogen; C:N = carbon to nitrogen ratio; dS/m=deciSiemen per meter; mg/L = milligrams/liter; mg/kg = milligrams/kilogram.
[2]Recommended range from Colorado State University Soil Testing Laboratory.
[2] Treatment Type: Treatment 1=Seed only (control); Treatment 2= Standard 70%Straw/30%Coir ECB; Treatment 3= 100% wool ECB; Treatment 4=50% wool/50% straw ECB; Treatment 5=30%wool70%straw ECB; Treatment 6=70% wool/30% straw ECB. Soil samples were collected from all 10 replications of each treatment and collectively placed in a single bag, a sample was then drawn from the bag and this composite was sent to a commercial lab for analysis.
[3] Pretreatment soil samples were collected from 4 random locations on the Transcend test slope in 2012 before experimentation, they were collectively placed in a single bag, a sample was then drawn from the bag and this composite was sent to a commercial lab for analysis.

The Transcend site was seeded in late June and monitored in October 2015. Seeded species did not establish during this period; therefore, the 2015 results are not presented. We present here results from 2016 (Table 27) and 2017 (Table 28) reflecting mean canopy cover by plant groups after one full growing season and two full growing seasons. Pairwise t-tests were used to determine significant differences among treatments within a plant group. Pairwise t-tests were used to determine significant differences between treatments within a plant group. That is, the t-tests compared one treatment to one other treatment with all combinations of treatments assessed. P-values are used to determine when treatments differ. P-values > 0.05 indicate the two treatments compared are not significantly different (i.e. the canopy cover is the same for both treatments). In 2016, there were no significant differences between treatments for any of the plant groups; P-values ranged from 0.229 to 1.0 for all t-tests in 2016 and 2017 (data not provided). Therefore, results suggest the differences in canopy cover by plant group were not statistically significant in either year.

Table 27: Mean percent canopy cover of plant groups by treatments at Transcend test site in 2016.

Treatment[1]	Description	Mean Percent Canopy Cover (%)		
		Seeded Native Grass	Desired Non-Seeded Species	Weed Species
1	Control A: Seed only (No ECB)	1.9	8.4	29.6
2	Control B: Standard 70% Straw / 30% Coconut ECB	4.7	3.1	31.8
3	100% Wool ECB	5.2	3.3	30.9
4	40% Wool / 60% Straw ECB	4.1	6.7	38.8
5	25% Wool / 75% Straw ECB	3.1	5.2	33.4
6	55% Wool / 45% Straw ECB	6.0	2.7	28.4

[1] Manufacturer: Treatment 2, 3, 4, 5 &6: Ero-Guard, Inc.

In 2016, seeded species had low canopy cover on all treatments after one growing season, ranging from 1.94% to 6.02% (Table 27). The desired non-seeded species also had low canopy cover at 2.66% to 8.36% and weed species were the dominant canopy cover on the treatments with 29.62% to 38.78% mean canopy cover (Table 27).

Table 28: Mean percent canopy cover of plant groups by rolled erosion control treatment or control at Transcend test site in 2017.

Treatment[1]	Description	Mean Percent Canopy Cover (%)		
		Seeded Native Grass	Desired Non-Seeded Species	Weed Species
1	Control A: Seed only (No ECB)	21.3	12.9	4.6
2	Control B: Standard 70% Straw / 30% Coconut ECB	28.0	18.5	6.0
3	100% Wool ECB	32.8	24.1	6.0
4	40% Wool / 60% Straw ECB	24.6	18.7	3.3
5	25% Wool / 75% Straw ECB	25.4	18.6	8.2
6	55% Wool / 45% Straw ECB	32.2	22.3	5.0

[1] Manufacturer: Treatment 2, 3, 4, 5 &6: Ero-Guard, Inc.

By the second growing season (June 2017) mean desired vegetative cover (seeded and desired non-seeded) had increased by approximately 20 and 40 percent, depending on the treatment (Table 27 versus Table 28). It was apparent (e.g. lack of broadleaf plants even in bare areas, curled plant stalks) that the field site had been sprayed with a broadleaf herbicide between the 2016 and 2017 field sampling. The herbicide product, rate and timing were unknown. The decrease in weed species canopy cover was complemented by an increase in grass species canopy. This is an expected result of herbicide treatments. Overall, the vegetation was well established for the south-facing slope that had low nutritional soils (Figure 20). The 100% wool ECBs still retained their integrity (Figure 21) while the remaining ECBs, including the straw-coconut control, had decomposed by an estimated 80% by June 2017.

Figure 20: Overview of the Transcend test slope vegetative cover, June 2017.

Figure 21: Close-up of the 100% wool ECBs deployed on test slope at Transcend, June 2017.

The 100% wool ECB and the ECB with the second highest wool content (treatment 6) had greater mean seeded native grass canopy cover than the standard straw coconut ECB's 28.0 mean percent canopy cover, 32.8% and 32.2%, respectively (Table 28). Similarly, these same two wool ECBs had higher mean canopy cover of desired non-seeded species, 24.1% and 22.3%, respectively, compared to the straw-coconut ECB's 18.5% cover. When combining the seeded and desired non-seeded species canopy covers, the 100% wool ECB's mean canopy cover of desirable species was highest of all ECB's at 56.9%, followed by the 55% wool/45% straw ECB's 54.5% cover of desired species. Both woolen ECBs exceeded the standard straw-coconut ECB's desirable species' mean canopy cover (46.5%) by 8 to 10 percentage points. However, pair-wise T-tests did not find any of these differences significant.

At the same time, in 2017 mean weed canopy cover decreased from 2016 as desired species became more established and after herbicide had been applied (Table 27 and Table 28). The test slope had inadvertently been treated with herbicide by a contractor who controls weeds for the entire Transcend facility and that perhaps could also explain the noticeably lower weed species' mean canopy cover.

Pairwise t-tests were conducted for the mean canopy cover of the combined seeded and desired non-seeded species of the various ECB treatments to determine if there were any statistically significant differences in the mean canopy cover of desirable species (Table 28). The only significant difference, p=0.028, was the mean canopy cover of the all desirable vegetation of the 100% wool ECB treatment (56.9%) was greater and the control treatment where ECB was applied (34.2%). All other p-values were greater than 0.11 indicating desirable species' mean canopy cover did not differ significantly between ECB treatments and with the control.

5.3 Conclusions

5.3.1 Silt Fence

The second generation of silt fence appeared to be the most durable and functional for capturing sediment. The wool felting provided an adequate medium for sediment filtration and the stitching improved strength and durability to last one year in field conditions. Future improvements of this product would include making the third generation of silt fence 100% biodegradable for decomposition on site. The plastic netting in the center of the wool material would need to be replaced with biodegradable fiber netting.

The third generation of silt fence needs further development. Only two sections were installed for less than a month before they were blown over by a storm event. It is possible that one layer of wool between a layer of burlap and a layer of netting on the downstream side, may be a better fence that is not overly restrictive of water flow and yet sufficiently filters sediment and can be produced at scale with existing ECB manufacturing equipment.

5.3.2 Wool Erosion Control Blankets and Compost along Highway 287

In general, the three control treatments (standard 70% straw / 30% coconut ECB, seed only, no seed) had significantly lower seeded grass canopy cover than all wool treatments except the four-pass needle punch ECB. This suggests that the wool material, regardless of type, may be providing some benefit to seeded perennial grasses during establishment. Non-seeded desired species established in relatively equal proportions among treatments which is probably a benefit of the randomized complete block design. Thus, conclusions are based on comparing the various treatments' mean canopy cover of seeded species and weedy species. Monitoring select treatments in 2017 at Highway 287 (Appendix A) confirms the superior performance of the wool ECB compared to standard straw/coir ECB and especially the unseeded control and seeded-only treatments. Quantitative measurements of vegetation canopy cover were made for select treatments, but statistical evaluation was not performed rendering the data advisory rather than demonstrative.

5.3.2.1 Wool / Straw ECBs made by an ECB manufacturer

5.3.2.1.1 Seeded grass canopy cover

The two best performing treatments (i.e. greatest seeded grass establishment) were the rolled wool/straw ECBs produced by Ero-Guard, Inc. The 100% wool ECB and 50% wool / 50% straw ECB had the greatest mean seeded grass canopy cover with 20.9% and 24.9%, respectively, after two years (Table 23). These two ECBs were developed for the project and produced by traditional geotextile manufacturing machinery that creates ECB rolls. One square meter test sections were cut from the rolls and applied to the experimental plots. The mean seeded grass canopy cover was four to five times higher for these two wool ECBs than the standard 70% straw / 30% coconut ECB used by MDT, which had a seeded grass mean canopy cover of 4.7% after two growing seasons (Table 23). These canopy cover differences were statistically significant ($P < 0.0001$) for both wool ECBs compared to the standard straw / coconut ECB (Table 24).

The project demonstrated that rolled ECBs are important for re-vegetation. The 100% wool, 50% wool / 50% straw, and 70% straw / 30% coconut ECBs all had higher mean seeded grass canopy cover after two years than the no seed (0.9% cover) and seed only (0.9% cover) controls. The

100% wool and 50% wool / 50% straw ECB treatments averaged greater than 20% canopy cover of seeded species within two years demonstrating how well the wool products performed at a site that previously failed to adequately establish vegetation after its construction in 2003. However, some caution should be used during data interpretation due to treatments being installed at different dates. Treatments 4, 10, and 11 were seeded and installed in May 2015 since the products hadn't been developed and delivered until that time. While all the other treatments were installed in fall 2014. The treatments installed in the fall experienced a high wind event and heavy erosion event that may have impacted seeded grass establishment. In addition, some research has indicated spring seeding produces higher seeded grass densities than fall seeding (Davis et al. 2016). Further testing of the woolen materials should occur when all treatments can be seeded and installed at the same time so weather and timing do not complicate the interpretation of results.

5.3.2.1.2 Weed canopy cover

In general, the two rolled wool ECBs made by Ero-Guard, Inc., and the standard straw / coconut ECB had lower weed canopy cover than seeded and non-seeded control treatments indicating that ECBs, regardless of the composition of their materials, provided some benefit in weed suppression. The mean weed canopy cover for 100% wool ECB, 50% wool / 50% straw ECB and 70% straw / 30% coconut ECB was 10.8%, 13.6%, and 17.7%, respectively (Table 23). However, these weed canopy cover values were not significantly different ($P = 1.0$; Table 24). However, when any of the mean weed canopy cover of these ECBs were compared to the no seed control (49.8%) or the broadcast seed control (47.1%), the differences were significant, with P-values varying from 0.0 to .019 (Table 24).

Field observations found the wool in the ECBs became felted when exposed to the weather. The felted wool material may have provided a barrier for broadleaf plants while allowing narrower grass leaves to penetrate the wool ECBs. Weed species had higher canopy cover than seeded species on all treatments except the 100% wool and 50% wool / 50% straw ECB.

5.3.2.2 Wool ECBs made by Montana wool mills

There were four wool ECBs developed with Montana wool mills for the project (Treatments 1 – 4; Table 19). These products were made by Thirteen Mile Lamb and Wool Company and Brookside Woolen Mill as individual pieces or batts, by either carding at different weights or by felting the wool via a different number of passes through a needle punch machine. Each batt was made to be approximately one square meter. All four of these test products were made of pure (100%) wool.

5.3.2.2.1 Seeded grass canopy cover

Three of the four pure wool ECB treatments had greater mean seeded grass canopy cover than the standard 70% straw / 30% coconut ECB. The standard ECB had 4.7% cover while the 44 g/m^2 and the 73 g/m^2carded wool ECBs had 9.7% and 8.6% seeded grass cover, respectively, and single pass needle punch ECB had 15.1% cover. However, the only product statistically different than the standard ECB was the single pass needle punch ECB ($P = 0.002$). The results suggest these wool products offered advantages for seed establishment and growth when compared to the standard straw-coconut ECB.

5.3.2.2.2 Weed canopy cover

In general, ECB treatments, including the standard straw / coconut ECB, at Highway 287, had lower weed canopy cover than the seeded and non-seeded control treatments indicating that the four different materials – no matter which type - provided some benefit in weed suppression.

All four wool ECBs had higher mean canopy cover for weedy species, 17.8%, 21.5%, 20.4% and 24.3%, then the standard straw / coconut ECB, 17.7% (Table 23). However, differences between these wool ECBs and the standard straw/coconut ECB weed cover were not statistically significant.

Field observations found the wool ECBs made from Montana wool mills became felted and shrank when exposed to the weather, most likely due to the wetting from precipitation - rain and snow - and the subsequent drying of the wool fibers. The felted wool material may have provided a barrier for broadleaf plants while allowing narrower grass leaves to permeate the wool material. Furthermore, weed presence may have impacted the seeded grass species' ability to establish.

5.3.3 Cut wool pieces mixed with compost

There was no statistical difference in the mean canopy cover of seeded grass species of the compost treatment (control) compared to the cut wool with compost treatment, 6.4% and 10.2%, respectively (Table 23). Similarly, no statistically significant differences were found for mean canopy cover of weeds or desired non-seeded species between the two treatments. This indicates that the project could not determine that cut wool pieces provided a benefit to plant establishment and growth when it is added to compost material.

5.3.4 Wool Erosion Control Blankets at Transcend

The seeded species were present on all treatment after two growing seasons. The desired non-seeded species also had a moderate canopy cover and were relatively evenly distributed between treatments so should not influence the results of seeded species establishment. Weed species were the dominant canopy cover on the treatments in 2016 and may have interfered with seeded species establishment. After herbicide treatment between 2016 and 2017, the mean canopy cover of seeded species, non-seeded desired species and all desired species increase for all treatments. Simultaneously, mean canopy cover of weed species decreased for all treatments in 2017.

The Transcend treatments were all seeded and installed at the same time which eliminates any bias for treatments that did not undergo the same weather events. Seeded grass should continue to develop and was monitored in 2017 to provide a better indication of how well the treatments establish seeded grasses and compare to each other after two growing seasons. After two growing seasons, there were no significant differences in vegetation canopy cover between treatments. The only exception was the 100% wool ECB had a higher canopy cover of all desired species than the control (no ECB / seed only).

6 COST BENEFIT ANALYSIS

This chapter develops and evaluates the effectiveness of woolen roadside reclamation products. The overall objective of the project is to evaluate wool products that can be used for roadside reclamation projects by the Montana Department of Transportation (MDT). The project seeks to develop and test potential wool products that can be easily produced as complementary or replacement products to existing traditional roadside products. Previous project objectives identified and develop wool products with potential for roadside applications (Chapter 3). The project conducted laboratory tests for promising wool products to determine whether they meet various performance specifications, as required by MDT and the Federal Highway Administration (Chapter 4). Another part of the project developed experimental plots to field test the woolen reclamation products and evaluate their relative effectiveness compared to standard products (Chapter 5).

The primary objective of this chapter is to report on the costs and benefits of the most promising lab and field tested wool products.

6.1 Methods

The project gathered and analyzed three different sources of information to develop reasonable cost estimates associated with producing the wool reclamation materials: wool market news, interviews, and price lists. All three sources of information were used to form the basis for the cost benefit analysis.

1. US Wool Market News: Information on the U.S. wool market is publicly available and produced by the U.S. Department of Agriculture (USDA) or state agricultural departments.
2. Interviews: This cost-benefit analysis was based on information gathered by interviews with wool mill owners and geotextile manufacturers. Since the project developed new wool reclamation materials and there has been no manufacturing of wool reclamation materials in North America, the research team interviewed wool mills and geotextile manufacturers for their cost of production.
3. Price lists: Price lists were used for commercially available products such as the standard ECB and compost used as controls in the field trials. Information on standard product costs was available by reviewing the literature and company sales information such as price sheets.

In addition, the following assumptions were used to develop this cost analysis:

- The wool reclamation products' manufacturing costs are projected, and based on future manufacturing and production reaching a scale that maximizes cost effectiveness. For example, this project required approximately 800 pounds of scoured, cut wool at $4.00/pound for the wool ECB products developed for use in lab and field tests. To decrease the cost of scoured, cut wool for wool ECB production, at least 2,000 pounds of wool would need to be bought and processed at once. If 2,000 pounds of wool were requested, then the cost of wool for ECB production could potentially be reduced to approximately $2.20/pound (Thayne Mackey, Brookside Wool Mill, personal communication, 10/17/16) if markets are similar in the future as they were when the wool was ordered for this project.

- The final wool product costs the same to ship from the manufacturer to the reclamation site as the standard product; therefore, manufacturer shipping costs are not included since they would vary widely depending on the shipping distance and quantity ordered.
- Projects costs are estimated based on future large scale wool processing, not small batches of wool batts that were developed for the project.
- If manufacturers provided a range of costs for a particular stage of production, then the middle of the range was used in the calculations.
- The wholesale prices are used for the analysis because retail prices were more variable depending on producer, quantity purchased, and the vagaries of supply and demand.

6.2 Results

6.2.1 Background: Wool Markets and Processing Costs

Since wool is integral to the development of the innovative products developed for this project, a brief understanding of wool production and costs is essential to understanding its viability as a component of these roadside reclamation products. The wool industry has witnessed a gradual decline in total numbers of sheep and lambs in the U.S. over the past decade (Table 29). In 2014, the U.S. had an inventory of 5.2 million sheep and lambs. According to the United States Department of Agriculture (USDA), Montana ranked eighth in the nation for sheep production with 220,000 head of sheep and lambs in 2014 (USDA, NASS. 2014).

Table 29: Sheep and lamb inventory (USDA, NASS 2014).

Sheep and Lamb Inventory	
Year	**1,000 Head**
2005	6,135
2006	6,200
2007	6,120
2008	5,950
2009	5,747
2010	5,620
2011	5,480
2012	5,365
2013	5,335
2014	5,210

As sheep inventory has shrunk in the U.S., so has wool production. In 2004, greasy wool (raw, uncleaned wool) production was approximately 37 million pounds. By 2012, greasy wool production had decreased to 27 million pounds across the nation (USDA, NASS. 2014). The latest data in the agricultural census indicates that Montana produced 1.8 million pounds of greasy wool in 2012. Scouring renders greasy wool weed seed free and hypoallergenic and is an important step in wool production. However, greasy wool is reduced to approximately half its weight in the scouring process as feces, oils, dirt and other impurities are removed (personal communication, Thayne Mackey, Brookside Woolen Mill, 2016).

It has been estimated that for every three pounds of greasy wool produced, one pound is unmarketable and stays on American farms and ranches (personal communication, Thayne

Mackey, Brookside Woolen Mill, 2016). Qualities that make wool unmarketable, include short fibers, the presence of hair, and inconsistent color. Therefore, of 27 million pounds of greasy wool produced in the U.S., approximately 9 million pounds of greasy wool (equating to 4.5 million pounds scoured wool) generates no income for wool producers. This 'waste wool' could be used for wool reclamation product production while having no effect on existing U.S. wool markets. In fact, use of the unmarketable greasy wool would benefit producers by generating additional income. Unmarketable greasy wool has been bought in Montana for $0.10-$0.20 per pound (personal communication, Thayne Mackey, Brookside Wool Mill, 2016). The 9 million pounds of waste wool in the U.S. would have a value of $900,000 - $1.8 million. In comparison, the national posted price (30-day weighted average) for the lowest grade of marketable greasy wool was $0.56 per pound in October 2016 (USDA, FSA 2016). The 27 million pounds of marketable wool in the U.S. has a value of $15.1 million. Thus, the unmarketable wool would have a value of 6 – 12% of the marketable greasy wool being sold today in the U.S. Other costs such as the amount purchased, transportation costs, and relative cleanliness (i.e. scouring needs) of waste wool should also to be considered in the total cost of using either unmarketable or market-based wool for erosion control products.

6.2.2 Wool and Wool / Straw Erosion Control Blankets

There were two types of wool ECB products developed by the project and tested in the field. One type manufactured by Montana wool mills was deployed only along U.S. Highway 287 (U.S. 287) near Three Forks, Montana. The second type was manufactured by a rolled ECB manufacturer in Minnesota and were field tested along U.S. 287 and at WTI's test slope at the Transcend experimental station in Lewistown, Montana.

6.2.2.1 Pure Wool ECB Batts produced by Montana wool mills

6.2.2.2 Descriptions of four pure wool ECB batts

Four wool ECB products that were developed and field tested by this project were produced by Montana wool mills. Two weights of carded pure wool batts and two types of needle punched pure wool batts were ultimately selected for field tests (see Chapters 3 and 4). Each batt was approximately one square meter in size and were deployed for field testing along U.S. Highway 287. For the results of vegetation establishment by each of the four treatments, see Chapter 5.

The project field tested the carded wool batts, at two different weights, 73 grams/meter^2 ((g/m^2) (2 ounce/yard^2 (oz/yd^2)) and 44 g/m^2 (1 oz/yd^2). The wool batts were made by Thirteen Mile Wool and Lamb Company of Belgrade, MT. Eleven replications of both types of carded batts were deployed by covering them with a jute netting and using sod staples adhere them to the ground. The netting was needed to give them strength and durability to the carded wool prototype since, by itself, the batts are quite frail, such as having a low tensile strength, as an ECB.

The two types of needle punched batts field tested along U.S. Highway 287 (Hwy 287) were either processed through a needle punch machine once in one direction or four times in two opposing directions. Each of these wool ECBs used approximately 73 grams/meter^2 (g/m^2) (2 oz/ yd^2) of wool. Needle punched batts were produced by Brookside Wool Mill of Malta, MT. Eleven replications of both types of needle punched batts were deployed by covering them with netting and using sod staples to adhere them to the ground. The netting was not necessary for the needle punched batts because they were a more durable material. However, we used the netting on all plots to maintain installation consistency for all applications along Hwy 287.

None of the four wool batts were considered a commercially viable product since Montana wool mills do not have equipment to produce large scale batt production (size and quantity) at the time of their production to produce rolls similar to the standard straw-coconut Type III ECB. Rather, they were developed and tested as prototypes to determine if relatively small amounts of wool could protect slopes from soil erosion and support the establishment of vegetation. Small amounts being crucial to keep wool ECBs cost competitive with coconut-straw ECB.

6.2.2.2.1 Costs associated with pure wool ECB batts

Using wool by itself for ECB batts is cost effective if using greasy non-marketable wool ($0.10 to $0.20 per pound) or wool bought at the low end of the market value ($0.56 per pound, USDA FSA 2016). Shipping of greasy wool to a wool mill with a scouring train and batt producing machinery would be additional costs to consider in the production of these pure wool ECB batt products. Scouring of greasy wool costs about $1.00 per pound, and only half the weight of the original wool remains after the cleaning process. If the wool source was located near the scouring and ECB production facility, shipping costs would be lower (Table 30).

Scoured wool for these products, if bought in quantity (at least 2,000 pounds) would cost approximately $1.10 approximately $1.10 to $1.20 per pound. The four wool ECBs each used 44 to 73 grams of clean weed seed weed seed free wool per square meter. Therefore, the wool used in production of wool ECBs by the Montana the Montana woolen mills would be $0.11 - $0.12 per square meter. Another cost is the woolen mills' time for mills' time for batt production. Thirteen Mile Wool produces and Brookside Woolen Mill sells wool batts for wool batts for $9 per pound. Therefore, the cost for pure wool ECB batt production is $0.90 - $1.44 per per square meter (Table 30 and

Table 31).

6.2.2.2.2 Further research and development of the wool ECBs

After the field tests, several factors were considered to determine the economic feasibility to further develop these four wool ECBs. First, carded pure wool is not strong enough to act as an ECB by itself. Thus, more materials and manufacturing processes would be required to make the "proof of concept" product viable commercially. This suggests that there will be more expenses of additional materials and additional manufacturing process(es) increasing the overall costs for pure wool ECBs. Machines that roll, stitch, or insert mesh netting to strengthen the wool batts are not typically found at a wool mill. Therefore, a mill would have to invest significant dollars to go into commercial wool ECB batting production. To adhere to typical dimensions of other commercial ECBs available on today's market and used by the transportation sector, the woolen mills' machines would have to be large enough to make rolls of wool ECB that are 2.5 m (8 ft) wide and at least 30 m (100 ft) long. Currently batt size production is about 1.2 m (4 ft) wide with variable lengths.

Second, each of the pure wool ECBs developed by the project shrunk in the field experiments, often to such an extent that after two years they provided minimal ground coverage (Figure 22). The shrinkage reduced their protection of the soil and vegetation (compare the two wool batts at the feet of the three workers in Figure 22 and the plot coverage of a wool batt in Figure 23).

Figure 22: Replications of erosion control products along U.S. Highway 287, Three Forks, Montana, October 2014. Plot dimension is one meter square and all treatments are covered with mesh netting stapled in place.

Figure 23: June 2016 field monitoring found shrinkage of a pure wool needle punched batt along U.S. Highway 287 near Three Forks, MT. The product initially covered the entire one square meter within the PVC frame

Table 30: Estimated costs of materials and processes for manufacturing erosion control materials.:

Product or Manufacture Process	Unit	Unit Cost (dollars)	Comments
Unmarketable Wool	pound	0.10 - 0.20	from individual producer ranches and farms
Greasy Wool	pound	0.50 - 0.80	from wholesale markets
Scouring Wool	pound	1.00 - 3.00	based on 1000-2000 pounds
Scoured Unmarketable Wool	pound	1.10 - 3.20	
Scoured Marketable Wool	pound	1.50 - 3.80	
Cut and shredded Wool	pound	1.00	
Scoured, Cut, Shredded Unmarketable Wool	pound	2.10 - 4.20	Used for rolled ECB production, cost scaled for 2,000-pound purchase
Scoured, Cut, Shredded Marketable Wool	pound	2.50 - 4.80	Used for rolled ECB production, cost scaled for 2,000-pound purchase
Straw	pound	0.06	from local farmers
Coconut Fiber (coir)	pound	0.30	imported in bales
Burlap	square meter	1.20	
Jute Netting + Manufacturing	square meter	0.49	

Table 31: Costs of various wool and standard non-wool ECB products, excludes production shipping costs.

Final Product[1]	Unit	Unit Cost (dollars)	Comments
Pure wool batting (no netting)	square meter	1.39 - 1.93	manufacturer cost – Thirteen Mile Wool and Brookside Woolen Mill[2]
100% Straw ECB[3]	square meter	0.52	manufacturer cost (includes shipping for production) – Ero-Guard[4]
70% Straw / 30% Coconut ECB	square meter	0.62	manufacturer cost (includes shipping for production) – Ero-Guard
100% Wool ECB[5]	square meter	2.69	manufacturer cost with scaling projection
50% Wool / 50% Straw ECB	square meter	1.18	manufacturer cost with scaling projection
25% Wool / 75% Straw ECB	square meter	0.84	manufacturer cost with scaling projection

[1] All ECBs have two layers of biodegradable jute netting and approximately 8 oz (0.5 lb) fill (straw, coir and/or wool) between the netting.
[2] Personal communication, Brookside Woolen Mill, Malta, MT, and Thirteen Mile Wool and Lamb website.
[3] All rolled ECB products include double layer of jute netting.
[4] Personal communication, Ero-Guard, Mapleton, MN.
[5] Based on scoured, cut and shredded unmarketable wool costing $3.15 per pound (mean value scaled for production; see Table 2). Does not include the shipping cost to get wool to the ECB manufacturer.

6.2.2.3 Wool / Straw rolled ECB

6.2.2.3.1 Descriptions of the four wool / straw rolled ECB products

Four wool / straw rolled ECB products that were developed and field tested by this project were produced by Ero-Guard of Mapleton, MN. The four products vary in the percent composition of wool and straw fill but all were stitched with the same double layer jute netting (Figure 24). The four field tested wool/straw rolled ECB products were:

- 100% Wool
- 55% Wool/45% Straw
- 40% Wool/60% Straw
- 25% Wool/75% Straw

The project field tested the two rolled ECB products (100% Wool, 55% Wool / 45% Straw) at the U.S. Highway 287 site, and all four wool / straw ECB at WTI's Transcend Research Facility. The rolled ECB products were 2.5 m (8 ft) wide and 30 m (100 ft) long. At the Highway 287 site, the ECB was cut into one meter squares for testing (Figure 22). At the Transcend site, the ECB was cut into 1.5 m wide by 5 m long plots to cover the height of the slope. Eleven replications were tested at Highway 287 and ten replications were tested at Transcend. In addition, each site tested the standard 70% straw / 30% coconut ECB product and broadcast seed only as control plots were tested (see Chapter 3).

The four wool/straw ECB are considered commercially viable products. The Minnesota-based ECB manufacturer (Ero-Guard) was able to substitute wool for coconut in the production of their ECB products. The wool / straw ECB is constructed using the same machinery as the standard ECB (Figure 26).

Figure 24: Example of wool combined with straw as fill between two biodegradable net layers in a rolled erosion control blanket.

Figure 25: Equipment that manufactures rolled ECBs, Ero-Guard, Mapleton, MN.

Figure 26: Close-up of a straw and jute net ECB manufacturing at Ero-Guard, Mapleton, MN.

6.2.2.3.2 Costs associated with rolled wool ECBs

Mixing wool with straw helps control the cost of the ECB products. To develop the product, we bought small amounts (400 pounds) of low quality wool that was scoured, cut, and shredded for $4/pound. Then we shipped the processed wool to the ECB manufacturer in Minnesota at a cost of approximately $1 / pound. Ero-Guard volunteered their time and equipment for the development of the wool / straw ECB. The four wool ECBs ranged from 59 to 302 grams (0.1 – 0.7 lbs) of wool per square meter. Therefore, the wool used in production of wool / straw ECBs would cost $0.32 - $2.20 per square meter using the medium cost when scaled for production. In addition, there is a straw component, jute netting and manufacturing cost. Overall, one square meter of a rolled wool/straw ECB cost $0.84 - $2.69 to produce, depending on the wool / straw composition (Table 31).

The highest costs were purchasing the wool, processing it at the woolen mill so it is ready for ECB production, and transportation to the ECB manufacturer, especially when purchasing and shipping relatively relatively small quantities of wool (e.g., 400 lbs). Several factors could reduce the cost of this product in the product in the future if scaled for production. These factors were incorporated in the costs listed in Table 30 Table 30 and

Table 31. If scoured, cut, and shredded wool for these products were bought and shipped in quantity (at least 2,000 pounds), then wool costs could be reduced to $2.10 to $4.80 per pound for wool (Table 30). For the research, shipping the wool from the wool mill to the ECB manufacturer cost $1/lb. If shipping in bulk, shipping could become more cost effective (shipping costs are not included in the wool ECB production costs in Table 30 and

Table 31). Furthermore, if ECB production could occur near the wool scouring mill, shipping costs would be even lower. Similar, to the manufacturing of other products, the more product produced could maximize its cost efficiency of scale.

6.2.2.3.3 Further research and development of the rolled wool ECBs

In comparison to the standard ECB products currently developed, the wool/straw ECB is $0.32 - $2.17 more expensive per square meter (Table 31). These figures excluded any production shipping costs. The rolled wool/straw ECB products would benefit from additional research on the ratio of wool / straw needed to provide a benefit to the vegetation while keeping wool component low enough to control product cost.

Our research found the 50% wool/50% straw ECB preformed equally well at establishing vegetation as the 100% wool ECB in the U.S. Highway 287 field trial. Lab tests for the 50% wool/50% straw ECB indicate it meets MDT's short-term ECB requirements (Chapter 4). Therefore, the 50% wool/50% straw ECB should be the product to further develop. The scaled cost for this wool ECB product is $1.18 per square meter, approximately double the cost of standard ECB. However, after two growing seasons at the U.S. Highway 287 site, the 50% wool/50% straw ECB averaged 15% more seeded grass cover than the standard 70% straw/30% coconut ECB product suggesting the added cost may have benefits with greater vegetation establishment. After one growing season at the Transcend site, there was no difference in the vegetation establishment of the wool verses standard ECB. An additional field season of data will be collected from the Transcend site to determine if the wool ECB had a cost benefit at both sites after two growing seasons.

6.2.2.4 Wool as an additive to compost

Pieces of cut wool were mixed with commercially available wood-based compost. The field tests comparing the compost with cut wool pieces to compost alone did not find any advantage of adding cut wool to compost. That is, adding wool to compost did not increase seeded species establishment (Chapter 5). Thus, conducting a cost benefit analysis for wool as an additive to compost is not necessary because the additional cost of adding wool had not vegetation establishment benefit.

6.2.2.5 Wool silt fences

6.2.2.5.1 Descriptions of the different wool silt fence products

There were three generations of wool silt fence product types developed for the project. The first generation of wool silt fence consisted of 100% biodegradable 244 g/m^2 (7 oz/yd^2) wet felted wool batts. The silt fence was manufactured by Sugar Loaf Wool Carding Mill. Each rectangular wool batt was approximately 106.7 cm (42 in) by 91.4 cm (36 in), and was subsequently sewed together by Custom Canvas Design of Bozeman, MT into a continuous roll of wool silt fence 106.7 cm (42 in) wide. The second generation of silt fence used the same felted wool product and included stitching to increase strength and longevity of the product. Custom Canvas Design of Bozeman, MT stitched at 10 cm (4 in) intervals into two layers of 140 g/m^2 (4 oz/yd^2) felted wool silt fence (Figure 19b). A plastic mesh net was stitched between the two layers of felted wool to increase strength of the resultant fence. A third generation 100% biodegradable silt fence was designed that consisted of two burlap sheets stitched together with cut and shredded scoured wool in the center, between the two layers of burlap. This was produced by Ero-Guard using the same machinery as the wool ECBs (Figure 25 and Figure 26).

Of the three versions of wool silt fence, the burlap-wool silt fence could conceivably be used in existing silt fence installation machinery, thus making installation expenses approximately the same.

There were two expenses not calculated for this evaluation. First, burlap-wool silt fence is 100 percent biodegradable, thus it would not have to be removed at the conclusion of construction projects like plastic silt fence often is required, providing a cost savings in labor for de-installation, compared to woven plastic silt fence. Similarly, there would be no plastic pollution of surface waters if the burlap-wool silt fence replaced woven plastic silt fence, thus the indirect costs for small bits of plastic potentially entering surface waters was also not evaluated.

6.2.2.5.2 Costs associated with wool silt fence

Costs associated with the development of the wool silt fence are provided in Table 32. The second generation of wool silt fence had the greatest longevity in the field tests but it also had the greatest cost for production, especially compared to the standard plastic silt fence. At this time, in the development of wool silt fencing, the three versions produced are 10 to 25 times more expensive than plastic woven silt fence (

Table 32). These make the products prohibitively expensive.

However, it should be noted that there are potential cost savings associated with wool silt fence versus the standard woven plastic silt fence being used by MDT. A 100% biodegradable silt fence made of wool and other natural materials would avoid the necessity of removal that the existing standard woven plastic silt fences require. It also would allow contracts to be closed sooner, since wool silt fences could be left in place. Thus, 100% biodegradable wool silt fences could provide some cost savings since they wouldn't need to be removed.

6.2.2.5.3 Further research and development of the wool silt fence

The third version of silt fence did not perform well in the field trials; however, the third generation of wool/burlap silt fence was much easier and less costly to produce at larger scales than the previous generation felted wool silt fence (Figure 27a and Figure 27b). This final version of silt fence could be produced on ECB machinery to keep costs lower than the felted wool silt fence developed for the project.

Table 32: Summary of wool silt fence costs.

Silt Fence Product & Description	Cost per linear foot of 30.5 cm-wide rolled material	Manufacturer	Fences tested by project
Standard woven plastic silt fence[1]	$0.26 - $0.37	Tenax®	Standard silt fence - control
Wool batts, wet felted, sewn together[2]	$5.93	Sugar Loaf Woolen Mill / Custom Canvas Design	1st Generation wool silt fence
2 layers of wool batts, wet felted, sewn together with strengthening stiches and plastic mesh in center[3]	$6.43	Sugar Loaf Woolen Mill / Custom Canvas Design	2nd Generation wool silt fence
2 layers of burlap with cut wool pieces in center layer	$3.75	Ero-Guard	3rd Generation wool silt fence

[1] Price varied, depending on retailer.
[2] Actual costs for project, experimental, not mass produced to benefit from economy of scale
[3] Estimated, based on first version, experimental, not mass produced to benefit from economy of scale
[4] Estimated by manufacturer after making only one roll of fence, based on cut scoured, shredded unmarketable wool at $3.15.

Figure 27: (a) Rolled silt fence constructed of two burlap layers sewn together with cut wool pieces as filler. (b) Backlit burlap and wool silt fence shows the lack of consistency in the distribution of the wool pieces in the center layer of the fence.

6.3 Conclusions

The following are the conclusions of the cost analysis:

- Wool production has decreased in the U.S. but using waste wool for reclamation products would still contribute an additional $900,000 – $1.8 million (6 – 12%) to the existing wool market.
- The cost of a pure wool batt is $0.90 - $1.44 per square meter to produce (within two layers of reinforcement netting); however, they did not improve seeded grass establishment in the field trials, and the products shrunk in size over time due to weather.
- The 50% wool / 50% straw ECB should be the rolled wool ECB product to further develop. The scaled cost for this wool ECB product is $1.18 per square meter, approximately double the cost of standard ECB. However, after two growing seasons at the U.S. Highway 287 field site, the 50% wool / 50% straw ECB averaged over 5 times more seeded grass canopy cover than the standard 70% straw / 30% coconut ECB after two years, 24.99% cover versus 4.7% cover, respectively. This suggests the added cost for wool ECB may be a benefit due to greater seeded grass establishment and cover.
- If you calculate the cost it took to generate each percent of seeded grass canopy cover per square meter of material at the US Hwy 287 site, then the 50% wool / 50% straw ECB is more cost effective than the 70% straw / 30% coir ECB:
  50% wool / 50% straw ECB: 25.0% canopy cover/$1.18/ m^2 = $0.05/percent cover/$m^2$
  70% straw / 30% coir ECB: 4.7% canopy cover/$0.62/ m^2 = $0.13/percent cover/$m^2$
  Restated, the calculations above indicated that it cost five cents to establish each percent of seeded grass canopy cover per square meter using the 50% wool / 50% straw ECB and it cost thirteen cents to establish each percent of seeded grass canopy cover per square meter using the 70% straw / 30% coir ECB. This makes it nearly three times more cost effective to use the wool ECB material than standard ECB if the goal is maximizing vegetative cover.
- After one growing season at the Transcend site, there was no difference in the vegetation establishment of the wool verses straw-coir ECB. An additional field season of data will be collected from the Transcend site to determine if the wool ECB had a cost benefit at both field sites after two growing seasons.
- Adding cut wool pieces to compost had no vegetation establishment benefit in the field trials; therefore, a cost analysis was not completed.
- The second generation of wool silt fence had the greatest longevity in the field tests but it also had the greatest cost for production ($6.43), especially compared to the standard plastic silt fence ($0.26 - $0.37).

The further development and production of rolled woolen reclamation products has merit, especially if they their noted improvement in vegetation establishment can continued to be demonstrated. The rolled products are the simplest to produce since they use existing ECB manufacturing equipment, and are the most cost effective of all the woolen reclamation products. Additional research could work on reducing the costs associated with scouring, shredding and shipping to make the product more cost competitive.

7 CONCLUSIONS

7.1 Laboratory Tests

Silt Fence

The heavier weight wool silt fence (244 g/m^2) was highly variable in mass per unit area, where as the lighter weight silt fence (140 g/m^2) and wool/burlap silt fence had a more even distribution of mass per unit area. Future development of the heavier weight wool silt fence should focus on a more even distribution of fiber to improve its strengths and eliminate weaker areas in the fence.

ECBs

Woolen ECB products exhibited variability in mass per unit area due to the uneven distribution of their straw and wool fill components. However, standard straw/coconut ECB also had variability in weight indicating that an even distribution of fill components may not be standard for rolled ECBs. If it is deemed important, future manufacturing improvements could standardize production of the new wool-straw ECB products for more uniform results.

The laboratory tests for tensile strength, C-factor and shear stress gave some indication of the wool / straw ECB's performance. These results should be viewed with some caution since only one replication of each test was performed due to the costs of such testing. The wool ECB:

- met MDT tensile strength standards for a short term (Type II B, C) or long term (Type III A) ECB,
- exceeded the minimum shear stress specified in the MDT standard specifications for short term ECB (Type II B) for low level events, but not for high level events, and was lower than the updated minimum shear stress level for short term ECB, and
- the C-factor was representative of a short- term ECB (Type II C).

In general, the wool/straw ECB was comparable to a short-term (Type II B or C) standard ECB commercially produced and used along MDT roadways. Future product development of the wool/straw ECB should focus on improving the shear strength at high flows so it meets all required Type III specifications.

The analytical laboratory tests showed that the wool-straw ECB has three features that may it improve roadside plant establishment and growth and reduce erosion:

- It has higher nitrogen levels than the standard materials (straw ECB or compost) which may provide a benefit to the establishment and growth of new vegetation over the long term as the wool decomposes.
- The wool/straw ECB has a relatively high percent saturation value which suggests it may hold on to more moisture than the traditional products.
- The wool/straw ECB has a low water holding capacity suggesting it may make the water more readily available for plant growth.

Wool as an Additive to Compost

Due to the total nitrogen level in wool and its water holding capacity, cut wool pieces as an additive to compost may improve plant establishment. Further research will be necessary to more fully understand the ideal mix of wool as an additive to compost.

7.2 Field Tests

Silt Fence

The second generation of silt fence appeared to be the most durable and functional for capturing sediment. The wool felting provided an adequate medium for sediment filtration and the stitching improved strength and durability to last one year in field conditions. Future improvements of this product would include making the second generation of silt fence 100% biodegradable for decomposition on site. The plastic netting in the center of the wool material would need to be replaced with biodegradable fiber netting.

Wool Erosion Control Blankets and Compost along Highway 287

In general, the three control treatments (standard 70% straw / 30% coconut ECB, seed only, no seed) had significantly lower seeded grass canopy cover than all wool treatments except the four-pass needle punch ECB. This suggests that the wool material, regardless of type, may be providing some benefit to seeded grass during establishment.

The two best performing treatments (i.e. greatest seeded grass establishment) were the rolled wool/straw ECBs produced by Ero-Guard, Inc. The 100% wool ECB and 50% wool/50% straw ECB had the greatest mean seeded grass canopy cover with 20.9% and 24.9%, respectively, after two years. These two ECBs were developed for the project and produced by traditional geotextile manufacturing machinery that creates ECB rolls. The mean seeded grass canopy cover was four to five times higher for these two wool ECBs than the standard 70% straw/30% coconut ECB used by MDT, which had a seeded grass mean canopy cover of 4.7% after two growing seasons.

The project demonstrated that rolled ECBs are important for re-vegetation. The 100% wool, 50% wool/50% straw, and 70% straw/30% coconut ECBs all had higher mean seeded grass canopy cover after two years than the no seed (0.9% cover) and seed only (0.9% cover) controls. The 100% wool and 50% wool/50% straw ECB treatments averaged greater than 20% canopy cover of seeded species within two years demonstrating how well the wool products performed at a site that previously failed to adequately establish vegetation after its construction in 2003.

In general, the two rolled wool ECBs made by Ero-Guard, Inc., and the standard straw / coconut ECB had lower weed canopy cover than seeded and non-seeded control treatments indicating that ECBs, regardless of the composition of their materials, provided some benefit in weed suppression.

Field observations found the needle punched and batted wool ECBs became felted when exposed to the weather. The felted wool material may have provided a barrier for broadleaf plants while allowing narrower grass leaves to penetrate the wool ECBs. Weed species had higher canopy cover than seeded species on all treatments except the 100% wool and 50% wool / 50% straw ECB.

In general, ECB treatments, including the standard straw / coconut ECB, at Highway 287, had lower weed canopy cover than the seeded and non-seeded control treatments indicating that the ECB materials – no matter which type - provided some benefit in weed suppression.

All four passes needle punched and batted wool ECBs had higher mean canopy cover for weedy species, 17.8%, 21.5%, 20.4% and 24.3%, then the standard straw/coconut ECB, 17.7%.

Cut wool pieces mixed with compost

There was no statistical difference in the mean canopy cover of seeded grass species of the compost treatment (control) compared to the cut wool with compost treatment, 6.4% and 10.2%, respectively. Similarly, no statistically significant differences were found for mean canopy cover of weeds or desired non-seeded species between the two treatments. This indicates that the project could not determine that cut wool pieces provided a benefit to the compost material.

Wool Erosion Control Blankets at Transcend

The seeded species were present on all treatment after two growing seasons. The desired non-seeded species also had a moderate canopy cover and were relatively evenly distributed between treatments so should not influence the results of seeded species establishment. Weed species were the dominant canopy cover on the treatments in 2016 and may have interfered with seeded species establishment. After herbicide treatment between 2016 and 2017, the mean canopy cover of seeded species, non-seeded desired species and all desired species increase for all treatments. Simultaneously, mean canopy cover of weed species decreased for all treatments in 2017.

The Transcend treatments were all seeded and installed at the same time which eliminates any bias for treatments that did not undergo the same weather events. Seeded grass continued to develop and was monitored in 2017 to provide a better indication of how well the treatments establish seeded grasses and compare to each other after two growing seasons. After two growing seasons, there were no significant differences in vegetation canopy cover between treatments. The only exception was the 100% wool ECB had a higher canopy cover of all desired species than the control (no ECB / seed only).

7.3 Cost Benefit Analysis

The following are the conclusions of the cost analysis:

- Wool production has decreased in the U.S. but using waste wool for reclamation products would still contribute an additional $900,000 – $1.8 million (6 – 12%) to the existing wool market.
- The cost of a pure wool batt is $0.90 - $1.44 per square meter to produce (within two layers of reinforcement netting); however, they did not improve seeded grass establishment in the field trials, and the products shrunk in size over time due to weather.
- The 50% wool / 50% straw ECB should be the rolled wool ECB product to further develop. The scaled cost for this wool ECB product is $1.18 per square meter, approximately double the cost of standard ECB. However, after two growing seasons at the U.S. Highway 287 field site, the 50% wool/50% straw ECB averaged over 5 times more seeded grass canopy cover than the standard 70% straw/30% coconut ECB after two years, 24.99% cover versus 4.7% cover, respectively. This suggests the added cost for wool ECB may be a benefit due to greater seeded grass establishment and cover.
- If you calculate the cost it took to generate each percent of seeded grass canopy cover per square meter of material at the US Hwy 287 site, then the 50% wool / 50% straw ECB is more cost effective than the 70% straw/30% coir ECB:

50% wool / 50% straw ECB: 25.0% canopy cover/\$1.18/ m^2 = \$0.05/percent cover/m^2
70% straw / 30% coir ECB: 4.7% canopy cover/\$0.62/ m^2 = \$0.13/percent cover/m^2

Restated, the calculations above indicated that it cost five cents to establish each percent of seeded grass canopy cover per square meter using the 50% wool / 50% straw ECB and it cost thirteen cents to establish each percent of seeded grass canopy cover per square meter using the 70% straw / 30% coir ECB. This makes it nearly three times more cost effective to use the wool ECB material than standard ECB if the goal is maximizing vegetative cover.

- After three growing seasons at the Transcend site, there were no statistically significant differences in the vegetation establishment of the various mix of wool-straw ECBs versus the standard straw-coir ECB. A cost-benefit analysis was not completed for this test site.
- Adding cut wool pieces to compost had no statistically significant vegetation canopy cover benefit in the field trials; therefore, a cost analysis was not completed.
- The second generation of wool silt fence had the greatest longevity in the field tests but it also had the greatest cost for production (\$6.43 per linear yard), especially compared to the standard plastic silt fence (\$0.26 - \$0.37).

The further development and production of rolled woolen reclamation products has merit, especially if their noted improvement in vegetation establishment can continued to be demonstrated. The rolled products are the simplest to produce since they use existing ECB manufacturing equipment, and are the most cost effective of all the woolen reclamation products. Additional research could work on reducing the costs associated with scouring, shredding and shipping to make the product more cost competitive.

8 RECOMMENDATIONS

Silt Fence

Further research and development of wool as a component of 100 percent biodegradable silt fence is warranted. However, today there are no requirements or regulations regarding silt fence biodegradability by state environmental or transportation agencies. Therefore, exploring the appropriate use of wool as a possible component of biodegradable silt fencing is hindered by a lack of policy requirements and market demand.

Wool as an Additive to Compost

Further research and development is necessary to more fully understand the ideal mix of wool as an additive to compost. Although this project tested only one wool-compost ratio and only one commercially available compost, it did find that mean seeded vegetation canopy cover was higher on compost incorporating wool pieces versus compost alone; however, the difference was not statistically significant. Future efforts should focus on exploring different wool - compost ratios, as well as experimenting with different types of commercial composts and mulches that MDT and other transportation agencies use. Ascertaining the proper wool-compost or wool-mulch ratios that prove to be beneficial and cost effective would benefit from further testing.

Woolen Erosion Control Blankets

Rolled erosion control blankets (ECBs) are used extensively for roadside reclamation that requires revegetation, slope stabilization and the prevention of soil loss and movement. Other techniques and products are also used, such as tackifiers, hydro mulch, etc. This project focused on ECBs since they appeared to readily incorporate wool fibers into their production.

Currently, ECBs used for such reclamation consist primarily of two layers of jute netting filled with straw (Type II ECB) or a straw-coconut mixture (Type III ECB). The coconut gives the ECB strength. This research project was able to successfully replace the coconut fibers (coir) with wool and the production machinery could also vary the amount, or the ratio of wool to straw, in the rolled ECB filler.

Results from this project were promising. The project provides strong evidence that the rolled woolen ECBs, commercially produced and developed for this project provide a benefit to the revegetation of slopes where ECBs are contemplated for use in a reclamation project.

It appears that wool in the filler, as it decomposes, provides nitrogen to the emerging plants. The soil samples from the project indicated a difference, but they did not have any statistical significance. However, it confirms what is intuitive, given wool is comprised of 16-17% nitrogen, as it breaks down, it provides nitrogen to the underlying soils and plants.

Although not quantified in the field, some of wool was still visibly present two years after the ECBs were deployed, as was the jute netting. Less so was the straw which either was decomposed or lost to wind and rain. Thus, the woolen ECBs were still functioning at some level as a shield for the slopes, giving at least some minimal protection to the soil from rain and wind.

In general, the mean canopy cover of seeded perennial grasses two years after deployment was greater when wool was used in the ECB versus the standard straw-coconut ECB. At one of the study sites the mean canopy cover differences were statistically significant; on the second study site, they lacked statistical significance.

We make the following recommendations for the use of wool-straw ECBs:

- It appears the ratio of wool to straw in the filler would not have to exceed 30 - 50% wool - straw to take advantage of the benefits of wool while keeping the woolen ECBs more cost effective.
- The wool - straw ECBs should be used on slopes steeper than 3 horizontal : 1 vertical (18.4 degrees slope).
- It is recommended wool - straw ECBs be used on roadsides with poor soils, particularly if nitrogen is limited, and/or soils that are rocky or clayey.
- It is recommended that wool - straw ECBs be used in arid areas or windy locations in Montana where water stress may challenge vegetation establishment and growth.
- Currently, the 50% wool-50% straw (the only product that was tested in a commercial laboratory by the project) met most Type II and Type III material standards required by MDT. It is recommended that future adjustments to a stronger netting might allow the woolen ECBs to meet all MDT material standards for these two ECB types.

9 REFERENCES

Advance Landscape Systems. 2011. EcoWool Mulch Mats. Online at: www.advancelandscape.co.nz.

Ament, R., Jennings, S. and P. Blicker. 2011. Steep cut slope composting: Field trials and evaluation. Report No. FHWA-MT/10-008/8196. Prepared for the Montana Department of Transportation, Helena, MT, USA. 102 pp.

Bohme, M., I. Pinker, H. Gruneberg, and S. Herfort. 2010. Sheep Wool as Fertilizer for Vegetables and Flower in Organic Farming. XXVIII International Horticultural Congress on Science and Horticulture for People. Acta Hortic. 933: 195-202.

Broda, J., Przybylo, S, Kobiela-Mendrek, K., Binias, D., Rom, M., Grzybowska-Pietras, J. and R. Laszczak. 2016. Biodegradation of sheep wool geotextiles. International Biodeterioration and Biodegradation 115: 31-38.

Cirtex. 2014. BioWool – Wool Matting. http://www.cirtex.co.nz/Cirtex-Solutions/Erosion-Control/BioWool---Wool-Matting.

D'arcy, J.B. 1990. Sheep management and wool technology, 3rd edition. New South Wales University Press, Kensington, NSW, Australia.

Davis, S., J. Mangold, A. Harvey. 2016. Mitigating priority effects of invasive plants during revegetation by altering planting date. Northern Rockies Invasive Plant Council Annual Conference, Boise, ID.

Ero-Guard. 2015. Rolled Erosion Control. Online information at: www.ramyturf.com/.

Geofabrics. 2015. Woolmulch. http://www.geofabrics.co.nz/products/erosion-mats/woolmulch.

Geotech. 2013. Terramat Wool Blankets and Collars. www.geotech.systems.co.nz

Gorecki, R.S. and M.T. Gorecki. 2010. Utilization of waste wool as substrate amendment in pot cultivation of tomato, sweet pepper and eggplant. Polish J. of Environ. Stud. 19 (5), 1083-1087.

Herfort, S. 2010. Use of sheep wool vegetation mats for roof greening and development of a sheep wool fertilizer. Presentation at World Green Roof Congress, Mexico City, August 10, 2010, Mexico City, Mexico

Mackey, T. 2016. Personal Communication with Brookside Wool Mill owner, 10/17/16.

Miller, R. G. 1981. Simultaneous statistical inference. Pages 6-8, 2nd ed., Springer Verlag, New York, NY.

MDT (Montana Department of Transportation). 2014. Standard specifications for road and bridge construction, 2014 edition. Helena, MT.

Montana Green Insulation. 2011. Online at: www.montanagreeninsulation.com/index.html.

Mueller-Dombois, D. and H. Ellenberg. 1974. Aims and Methods of Vegetation Ecology. John Wiley and Sons, New York, NY.

Simpson, W.S. and Crawshaw, G.H. 2002. Wool: Science and technology. Woodhead Publishing Limited, Cambridge, England, UK.

Terra Lana. 2014. Mulchmat. Online at: www.terralana.co.nz/mulch-mat.html.

Thermafleece. 2014. Thermafleece original natural insulation. Online at: http://www.thermafleece.com.

Twool. 2012. Garden twine and lots more made from Dartmoor wool. http://www.twool.co.uk.

USDA, NASS (United States Department of Agriculture, National Agricultural Statistics Service). 2014. 2012 Census of Agriculture, United States, Summary and State Data, Volume 1, Geographic Area Series, Part 5.1, AC-12-A-51.

USDA, FSA (United States Department of Agriculture, Farm Service Agency). 2016. Weekly Wool Market Price, October 18, 2016. Online at: https://www.fsa.usda.gov/Internet/FSA_EPAS_Reports/wamrpt101816.pdf.

U.S. Department of Transportation, Federal Highway Administration, Federal Lands Highway. 2014. Standard specifications for construction of roads and bridges on federal highway projects, FP-14. U.S. Government Printing Office, Washington, DC. Available at: http://flh.fhwa.dot.gov/resources/specs/fp-14/fp14.pdf.

United Nations. 2012. Food and Agriculture Organization of the United Nations, FAOSTAT. Available online at: http://faostat3.fao.org/faostat-gateway/go/to/home/E.

Upton, C. 2003. The Sheep Production Handbook. Prepared by the American Sheep Industry Association, Inc., Englewood, CO, USA.

Wild Valley Farms. 2016. Wild Farms Valley website. Available online at: www.wildvalleyfarms.com/wool-pellets.html.

10 APPENDIX A: HIGHWAY 287 VEGETATION MONITORING 2017

Vegetation cover was measured at selected treatments at the Highway 287 research plots on July 6, 2017. Overall vegetation condition on the plots was good reflecting adequate spring moisture and a rain event during June that may have exceeded 2 inches over 48 hours. A June 13, 2017 site visit by Stuart Jennings, Phil Johnson and Rob Ament found very wet soil conditions that resulted in muddy soil observed deeper than 2 inches. Based on a visual inspection of all treatment types (Appendix A Table 33), it was decided to only monitor treatments 6 through 11.

Appendix A Table 33. Treatments selected for vegetation cover and soil monitoring in 2017, U.S. Highway 287, Three Forks, MT.

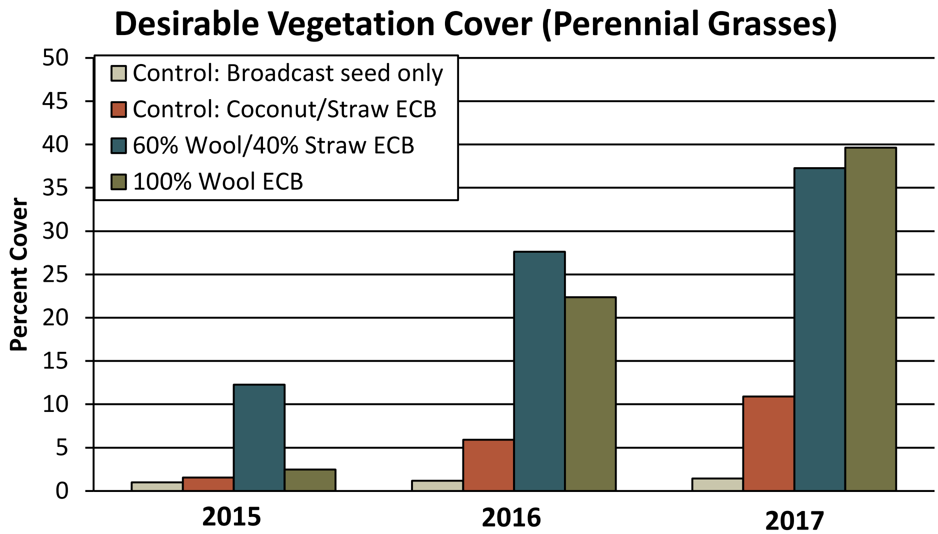
Treatment Number	Descriptions of Experimental and Control Treatments	July 2017 Assessment
1	Carded Wool Blanket (73 g/m^2; $2oz/yd^2$)	No
2	Carded Wool Blanket (44 g/m^2; $1oz/yd^2$)	No
3	Needle punched (one pass) felted wool blanket	No
4	Needle punched (four pass) felted wool blanket	No
5	Compost with cut wool; 40:1	No
6	Control: Standard 70% straw/30% coconut ECB	**Yes**
7	Control: Compost	**Yes**
8	Control: Broadcast seed only	**Yes**
9	Control: No Seed or treatments	**Yes**
10	100% wool ECB	**Yes**
11	60% wool/40% straw ECB	**Yes**

Measurements of vegetative canopy cover by plant species were recorded at each of the 11 plots for the six selected treatments. Vegetative canopy cover was defined as the vertical projection of the crown or shoot area of a species projected on the ground as a percent of the reference area (Mueller-Dombois and Ellenburg 1974). For analysis, species were grouped as desirable perennial grasses, desirable forbs, and undesirable species (weeds).

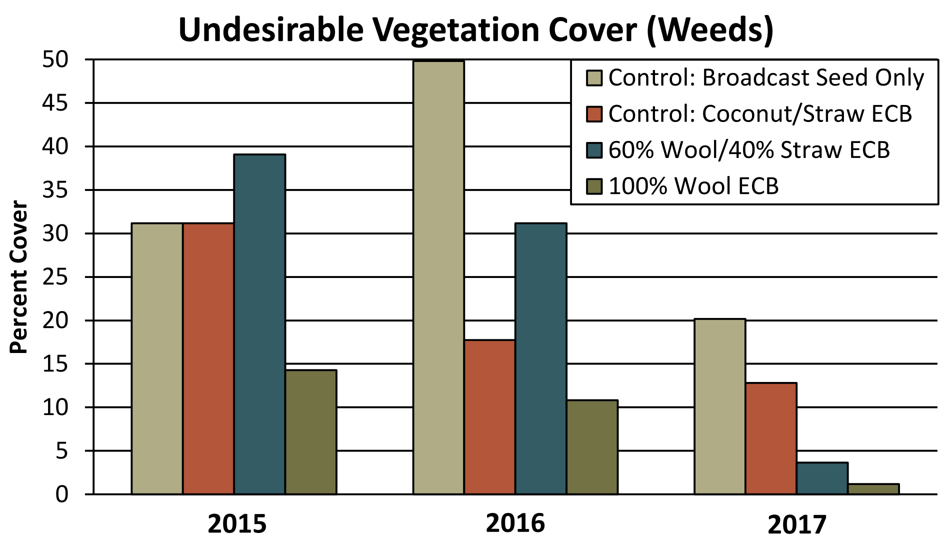
Appendix Table 34 summarizes average vegetative cover by species for the four control treatments, the 60% wool/40% straw ECB, and the 100% wool ECB in the first three growing seasons (2015-2017). The averages were calculated from the cover data collected at each of the 11 plots from each treatment type. The data show little differences in desirable vegetation and weedy species cover in the first growing season (2015). By the second growing season (2016), desirable grass cover in the 60% wool/40% straw ECB and the 100% wool ECB increased (22.4% and 27.6%, respectively), while cover in all four control types remained relatively low (1.5%, 2.5%, 1.0%, and 2.5%). In that same year, weed cover was variable across the treatment types, though total weed cover in the 100% wool ECB was the lowest of all treatments (10.8% in 2016). In 2017, with both wool ECB products had higher canopy cover of desired grass than the straw/coir ECB treatment and had lower weed cover. In 2017, the control treatments had higher canopy cover of desired forbs. Appendix Figure 28 and Appendix Figure 29 illustrate canopy cover trends in the first three growing seasons. Statistical analyses were not performed on 2017 data and were not tested for statistical significance.

Appendix Table 34. Average vegetative canopy cover by treatment type in monitoring years 2015, 2016, and 2017.

Assessment Year	**Treatment Number**	**Treatment Name**	Sheep fescue	Thickspike wheatgrass	Canada wildrye	Canada bluegrass	Western wheatgrass	Green needlegrass	Indian ricegrass	Crested wheatgrass	Needle and thread	**Desirable Grass Total**	Annual sunflower	Blanketflower	Vetch Spp.	Yellow sweetclover	**Desirable Forbs Total**	Flixweed	Dandilon	Prickly lettuce	Tumble mustard	Curlycup gumweed	Japanese brome	Cheatgrass	Goatsbeard	Kochia	Alyssum	Camelina	Penny cress	Prostrate knotweed	Russian thistle	**Weeds Total**
2015	6	Control: Coconut/Straw ECB	0.1	0.4	0.1	0.2	0.7	--	--	0.1	--	**1.5**	--	--	--	0.2	**0.2**	--	--	--	--	--	--	0.1	--	30.5	--	--	--	--	0.6	**31.2**
	7	Control: Compost	--	0.8	0.4	--	0.8	--	--	0.5	--	**2.5**	0.1	--	--	0.1	**0.2**	--	--	--	--	--	--	--	--	44.8	--	--	--	--	1.1	**45.9**
	8	Control: Broadcast seed only	--	0.4	0.2	0.1	0.3	--	--	0.1	--	**1.0**	--	--	--	0.2	**0.2**	--	--	--	--	--	--	0.1	--	30.5	--	--	--	--	0.6	**31.2**
	9	Control: No Seed or treatments	--	0.4	0.2	--	0.1	--	--	0.3	--	**0.9**	--	--	--	0.1	**0.1**	--	--	--	--	--	--	--	--	16.8	--	--	--	--	0.5	**17.4**
	10	100% wool ECB	--	1.4	--	--	1.0	--	--	0.1	--	**2.5**	--	--	--	0.1	**0.1**	--	--	--	--	--	--	--	--	13.3	--	--	--	--	1.0	**14.3**
	11	60% wool/40% straw ECB	1.2	6.6	1.1	1.3	1.5	0.5	0.2	--	--	**12.3**	--	0.1	--	1.2	**1.3**	--	--	1.5	23.0	--	2.1	0.5	0.5	9.3	0.8	1.3	--	0.1	--	**39.1**
2016	6	Control: Coconut/Straw ECB	1.5	2.7	0.4	0.1	0.9	0.3	--	--	--	**5.9**	--	--	--	8.8	**8.8**	0.1	--	0.5	6.3	--	1.3	1.6	0.6	6.5	0.1	0.6	--	--	0.1	**17.7**
	7	Control: Compost	1.5	3.2	0.8	0.8	0.5	--	--	0.1	--	**7.0**	0.1	--	--	1.8	**1.9**	--	0.1	0.2	19.1	--	1.1	0.5	0.3	13.2	0.7	0.2	--	--	--	**35.4**
	8	Control: Broadcast seed only	0.3	0.5	--	0.1	0.2	0.1	--	--	--	**1.2**	0.5	0.1	0.1	4.7	**5.5**	--	--	0.5	1.4	--	0.5	--	0.3	43.5	0.2	0.2	0.1	0.1	0.5	**47.1**
	9	Control: No Seed or treatments	0.3	0.5	--	0.1	--	0.2	--	--	--	**1.1**	0.3	0.1	--	6.4	**6.7**	--	--	0.5	1.0	--	2.1	0.1	0.3	45.5	--	0.1	--	--	0.2	**49.8**
	10	100% wool ECB	11.5	8.4	0.4	0.6	1.3	--	--	0.1	0.1	**22.4**	--	--	--	1.4	**1.4**	--	--	--	2.5	--	0.2	--	0.2	6.3	1.5	--	--	--	0.2	**10.8**
	11	60% wool/40% straw ECB	12.1	12.5	0.1	--	2.7	0.2	--	0.1	--	**27.6**	--	--	--	0.2	**0.2**	--	--	--	--	--	--	0.1	--	30.5	--	--	--	--	0.6	**31.2**
2017	6	Control: Coconut/Straw ECB	5.1	5.0	--	--	0.2	0.6	--	--	--	**10.9**	--	--	--	4.5	**4.5**	--	--	0.4	2.7	--	2.4	1.8	--	4.9	0.6	--	--	--	--	**12.8**
	7	Control: Compost	2.8	4.6	0.5	0.5	1.4	0.1	--	--	--	**10.0**	--	--	--	6.1	**6.1**	--	--	0.5	3.0	--	4.3	--	--	6.5	0.8	--	--	--	--	**15.0**
	8	Control: Broadcast seed only	1.0	0.5	--	--	--	--	--	--	--	**1.5**	--	--	--	13.5	**13.5**	--	--	0.4	0.1	1.8	4.3	--	--	12.6	1.0	--	--	--	--	**20.2**
	9	Control: No Seed or treatments	5.4	0.6	--	0.5	0.1	--	--	--	--	**6.5**	--	0.1	--	14.2	**14.3**	--	--	0.5	--	--	6.8	0.3	--	11.4	0.7	--	--	--	--	**19.6**
	10	100% wool ECB	37.3	2.1	--	--	0.1	0.2	--	--	--	**39.6**	--	--	--	--	**--**	--	--	--	--	--	0.1	--	--	0.5	0.5	--	--	--	--	**1.2**
	11	60% wool/40% straw ECB	29.2	7.5	--	--	0.5	0.1	--	--	--	**37.3**	--	--	--	0.1	**0.1**	--	--	0.1	--	--	0.1	--	--	2.9	0.5	--	--	--	--	**3.6**



Appendix Figure 28. Desirable vegetation cover from 2015-2017 for selected treatment plots.



Appendix Figure 29. Undesirable vegetation cover from 2015-2017 for selected treatment plots.

In conclusion, the wool treatments appears to establish grass and exclude weeds better than the conventional straw/coir treatment. After the first growing season, desirable grass cover increased in the wool ECB plots; and was greater than all control treatments in the third growing season. Also by the third growing season, a clear trend of weed exclusion emerged, with the lowest occurrences of weedy forbs and annual grasses in the 60% wool ECB and the 100% wool ECB treatments.