Water Air Soil Pollut (2017) 228: 232
DOI 10.1007/s11270-017-3374-9

Erosion from a Cross-Country Natural Gas Pipeline Corridor: The Critical First Year

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Received: 9 January 2017 / Accepted: 17 April 2017 / Published online: 5 June 2017

Abstract Sediment losses as concentrations and yields were measured for a year from 12 segments of a newly constructed (buried) natural gas pipeline on the US Forest Service's Fernow Experimental Forest in West Virginia. Pipeline segments were separated by waterbars which served as drainage features. Six segments were northwest-facing, and six were southeast-facing. Three segments on each aspect were seeded with warm season native herbaceous species at rates used by the Forest Service (1×). All remaining segments received seeding at three times that rate (3×). Forest Service-established rates of fertilizer, lime, and straw mulch were applied to all segments. Sediment concentrations and yields generally were highest at the start of the study, respectively, averaging approximately 1660 mg L^{-1} and 340 kg ha^{-1} during the first 3 months following completion of corridor reclamation, but they were less than from nearby less-steep forest road corridors. Concentrations and yields fell significantly after the first 3 months; declines were attributed to revegetation on the ROW. At the end of the first growing season, vegetative cover on all segments ranged from 55 to 79%, with no differences between seeding rates. Mean runoff was significantly higher on the northwest-facing segments than on the southeast-facing segments, but runoff volumes did not decrease on either aspect in concert with loadings or concentrations. Higher runoff on the northwest-facing segments may have been due to clay-skinned peds in subsurface soil that limited vertical drainage. Even with a heavy straw mulch cover on the right-of-way, the timing of the highest sediment losses immediately following pipeline construction suggests that implementation of additional surface-protection best management practices could be beneficial until vegetation is reestablished.

Keywords Energy transmission · Forests · Ground cover · Native seeding · Pipeline runoff · Sediment concentrations · Sediment yields

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1 Introduction

During the past decade, natural gas development underwent a boom as many deep reserves became available to production due to the combination of modernization of hydraulic fracturing technologies and greater investment in publically traded energy funds. Even with recent downturns in natural gas prices and the glut in the market, many gas fields are still being developed in the USA as domestic long-term use and exports of natural gas are expected to increase in the future (Energy Information Administration 2016).

Increased availability of natural gas requires infrastructure for product transport, with much of the transportation being accomplished through pipelines. Given the magnitude of recent and expected increases in natural gas production, it is not surprising that gas pipeline construction also is undergoing substantial expansion. For example, in 2005, 1854 km of gas pipeline were constructed in the USA (Energy Information Administration 2009), which resulted in a total length of approximately 2,396,702 km of pipelines (United States Department of Transportation 2015). Another 7662 km were planned for construction in 2008, and construction length in 2012 was projected to be more than 5.5 times the length constructed in 2011 (Smith 2013). Nearly 138,000 km were added to the US natural gas pipeline infrastructure from 2005 to 2013 (United States Department of Transportation 2015).

While pipelines can be installed within existing infrastructure, such as within existing road rights-of-ways, the high cost of pipeline construction (Smith 2013) typically makes cross-country installation much more economically attractive because more-direct routes are used. In hilly or mountainous terrain, cross-country installation can result in long lengths of disturbance on very steep slopes. Pipelines that run up and down steep hillsides are particularly a concern for soil loss, since slope plays such an important role in erosion processes and rates (Quansah 1981; Bryan and Poesen 1989; Chaplot and LeBissonnais 2000). However, there has been very little published research describing soil losses from natural gas pipelines (Harrison 2011), especially during and immediately following their construction, even though these are the periods during which soil losses are expected to be highest, based on road-corridor construction experiences (Cerdà 2007; Stedman 2008). Consequently, this study was designed to examine soil losses from a newly constructed cross-country pipeline and the influence of vegetation establishment on soil losses.

2 Materials and Methods

The study was performed from June 2009 through June 2010 in the Fernow Experimental Forest (FEF), which is located in north central West Virginia (USA) within the US Forest Service's Monongahela National Forest (MNF). The FEF is located within the Allegheny Mountain section of the unglaciated Allegheny Plateau. Annual precipitation, as determined from a permanent Forest Service weather station on the experimental forest near the pipeline corridor, averages 148 cm and is distributed relatively evenly throughout the year.

The pipeline itself is a small (~9 cm) diameter gathering line that eventually connects to a transmission line. Consequently, the pipeline right-of-way (ROW) is only approximately 9 m wide, and was constructed using a bulldozer and track-mounted excavator. Approximately one third of the length on the FEF was on a ridge-top, one third was on a northwest-facing hillside, and one third was on a southeast-facing hillside. All overstory trees were felled and the stumps removed prior to trench excavation, and the pipeline was buried approximately 76 cm below the soil surface.

Waterbars (Fig. 1), also called berms or diverter berms outside the USA (Morgan et al. 2003; Morgan and Hann 2005), were constructed for drainage control using a backhoe following pipeline installation and backfilling. Waterbar spacing (i.e., from crest to crest of adjacent waterbars) was dependent upon the slope of the ROW, as defined by MNF best management practice (BMP) requirements for pipelines. The slopes of the study segments of pipeline corridor were greater than 20% slope, so the waterbars were designed to be no more than 15 m apart, though one segment did not meet this criterion as adjacent waterbars were approximately 19 m apart.

Fig. 1 Photograph of a waterbar on the pipeline corridor used to control drainage. Note the base of the waterbar is below the surface of the ROW and the crest of the waterbar is above the surface of the ROW. The vertical distance between the base and crest of the waterbar is approximately 41 cm; the length of this waterbar is 8.3 m. This photograph was taken immediately after construction before seed, fertilizer, and mulch were applied

From late April through mid-May 2009 following waterbar installation, seed, fertilizer, lime, and whole straw mulch (i.e., straw was not chopped or hydromulched) were applied by hand to the entire length of the pipeline corridor. Fertilizer (10-20-10) was applied at a rate of 672 kg ha^{-1} (600 lb ac^{-1}), and lime and straw mulch each were applied at the rate of 4.48 metric tons ha^{-1} (2 ton ac^{-1}). While given the option to customize fertilizer and lime rates based on soil test results, the pipeline contractor instead opted to use the aforementioned rates that the Forest Service has established as being suitable for forest soil conditions in the area. A warm season native seed mixture of grasses and legumes was used on the entire corridor length within the MNF boundary (see Table 1 for species and rates). Annual ryegrass (*Lolium multiflorum*), oats (*Avena sativa*), and partridge pea (*Chamaecrista fasciculate*) were designed to serve as nurse crops to provide quick vegetative cover, giving the other more slowly developing, perennial species (Table 1) time to become established. Partridge pea and Canada milkvetch (*Astragalus canadensis*) are nitrogen fixers. This seed mixture was adapted from previous mixtures developed on the MNF after testing under a variety of climate and other physical conditions; seed mixture adaptation involved replacement of some species by others deemed suitable, due to seed availability constraints in spring 2009.

Based on a reconnaissance of the pipeline corridor, six waterbar segments were selected for study on each of the northwest-facing and southeast-facing aspects (Fig. 2). The segments were selected based on accessibility for equipment installation and sampling, and slope similarity between the aspects. A waterbar segment is defined as the area composed by the width of soil disturbance with a length extending from crest to crest of adjacent waterbars. Physical characteristics determined from surveying each of the study waterbar segments are given in Table 2. Since waterbars are installed at an angle (~30°) across the right-of-way width to encourage drainage, and waterbars were not consistently designed to drain to only one side of the corridor, the mean contributing length of each segment was calculated from four length measurements: along both outside edges of the ROW and one located approximately one third of the way in from each edge.

Table 1 Species information and seeding rates (kg ha^{-1}) for seed sowed on the cross-country pipeline ROW following construction

Common name	Scientific name	Function/type	Seeding rate
Annual rye grass	*Lolium multiflorum*	Nurse crop	33.6
Partridge pea	*Chamaecrista fasciculate*	Nurse crop	2.24
Oats	*Avena sativa*	Nurse crop	3.36
Canada milkvetch	*Astragalus canadensis*	Perennial	2.24
Little bluestem	*Schizachyrium scoparium*	Perennial	3.36
Autumn bentgrass	*Agrostis penennans*	Perennial	4.48
Deer tongue	*Panicum clandestinium*	Perennial	6.72
Total			56.0

One objective of this study was to examine the influence of seeding rates on erosion. Immediately following the initial seeding and prior to the fertilizer, lime, and mulch application, additional seed of the original mixture was hand applied to select (see below) waterbar segments on both aspects. The additional application was double the seed mass of each species used in the initial application, resulting in a total of three times the initial rate (i.e., initial rate + two times the initial rate). Henceforth, the lower and higher rates will be referred to as 1× and 3× seed rates, respectively. Identical fertilizer, lime, and mulch rates were used on the 1× and 3× seed rate segments. In neither case was the seed tamped or pressed (e.g., cultipacker) onto or into the soil surface, as it is MNF policy to minimize compaction on pipeline ROW and trench surfaces to encourage infiltration.

Because the contributing lengths of the individual pipeline corridor segments varied (Table 2), northwest-facing and southeast-facing waterbar segments of similar lengths were paired (Table 3) for assigning seeding rates. Contributing length, rather than segment area was used for pair assignment, because surface runoff and erosion were expected to occur primarily longitudinally along the pipeline corridor. Three waterbar segments were selected randomly from the northwest-facing sections; these segments and their southwest-facing pairs were used to study the influence of seeding rates on erosion (Table 3).

Soil characteristics associated with each aspect were described by the MNF Soil Scientist based on soil pits excavated at two locations immediately adjacent to the pipeline ROW but outside the influence of pipeline disturbance. Each soil pit was located at the approximate

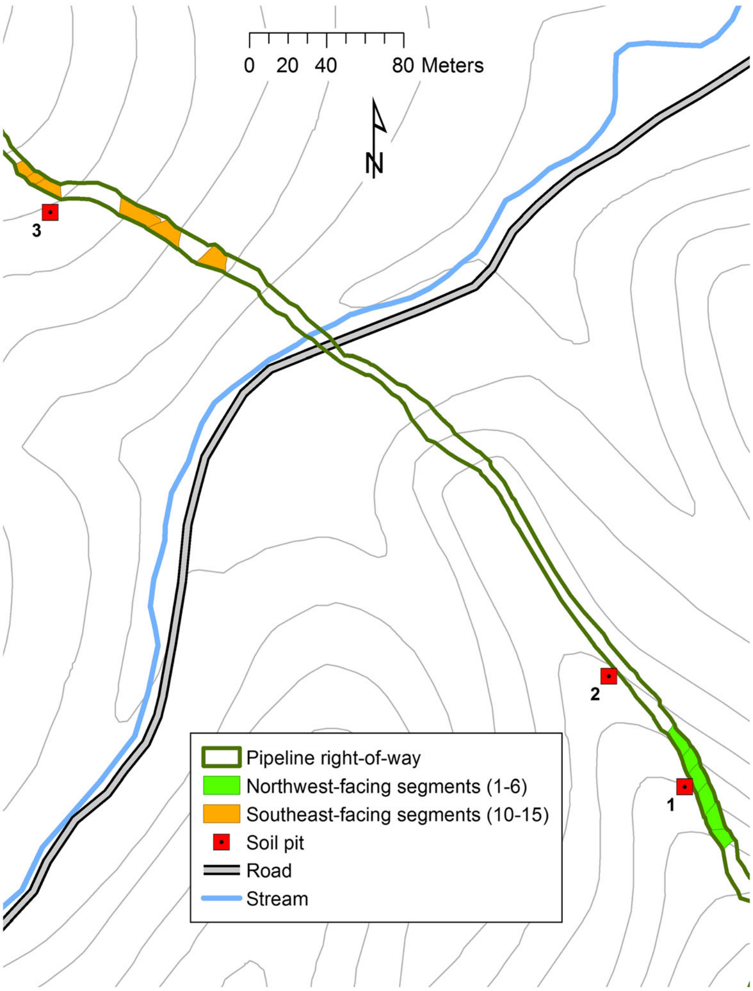

Fig. 2 Map showing relative locations of the northwest-facing and southeast-facing waterbar segments and locations of soil pits used to describe the soils associated with each aspect

Table 2 Area, mean slope, aspect, and mean contributing length for each of the 12 pipeline segments

Segment	Surface area (m^2)	Mean slope (%)	Mean contributing length (m)
Northwest-facing			
1	85.45	50.0	8.51
2	110.72	51.5	10.88
3	111.61	43.8	10.86
4	100.30	45.7	9.95
5	83.08	46.8	7.82
6	102.23	44.4	13.74
Southeast-facing			
10	148.49	57.0	10.77
11	154.96	57.9	13.72
12	176.34	30.2	19.19
13	95.62	67.6	11.58
14	46.67	68.4	4.61
15	68.01	48.5	7.33

longitudinal mid-point of the northwest- and southeast-facing segments (Fig. 2, soil pits 1 and 3; Appendix 0, locations 1 and 3). The soil on the northwest-facing

Table 3 Paired segments from the northwest- and southeast-facing aspects, and relative seed rates they received; 1× seed rates correspond to the rates described in Table 1; 3× seed rates are equivalent to three times the rate given in Table 1 for each species

Northwest-facing segment	Southeast-facing segment	Seed rate
1	10	1×
2	13	3×
3	11	1×
4	15	3×
5	14	1×
6	12	3×

segments is a Shouns fine-loamy, mixed, semiactive, mesic Typic Hapludults and on the southeast-facing segments the soil is Calvin loamy-skeletal, mixed, active, mesic Typic Dystrudepts. At this site, the Shouns soil contains a drainage-limiting layer. Both soils are derived from the Hampshire formation, which in West Virginia is a non-marine, Devonian era reddish sedimentary geologic formation composed of siltstone, sandstone, and conglomerate (https://mrdata.usgs.gov/geology/state/sgmc-unit.php?unit=WVDhs%3B0). These soils are stable and not subject to landslides, though the Shouns description indicates the occurrence of a small slide (i.e., colluvial movement; the BC horizon interbedded between Cr horizons) in the geologic past. A third soil pit (Fig. 2, pit 2; Appendix 0, location 2) just downslope of the northwest-facing study segments also was described. It is mentioned here because it provides information used to interpret results described later in this paper.

To measure sediment losses, surface runoff was collected at the outlet of the down slope waterbar in each segment. Pre-fabricated metal 0.61-m H-type flumes or locally constructed pressure-treated wooden flumes were installed at the waterbar outlet to direct surface runoff to collection devices. The wooden flumes were constructed of similar dimensions as the metal flumes, and were coated with several layers of marine varnish and the seams sealed with silicone caulk to prevent water or sediment leakage. The area between the soil of each waterbar outlet and each flume was filled with hydraulic cement to prevent water piping behind and under the flumes (Fig. 3). All flumes were further secured to the ground with wooden stakes.

Runoff passing through each flume was diverted by gravity to a high-density polyethylene collection tank downslope. The tanks had either 473-L (125-gal) or 378.5-L (100-gal) capacities, and each had a valve at its base to allow sampling and 3.78-L (1-gal) gradations on the outer surface, which were used to determine the runoff volumes. Collection of runoff began on June 12, 2009, which corresponded to the first storm event after all tanks were installed. Sampling continued for 1 year from that date. Samples were collected after individual precipitation events when possible; however, a portion of the samples included multiple events, particularly those occurring on weekends. The date, time, tank volume, and waterbar segment numbers were recorded at the time of sampling.

Fig. 3 Hydraulic cement was used to connect the waterbar outlets to the flumes, which prevented water from piping behind and under the flumes. The wooden stakes that secured this wooden flume in place and the collection device at the flume outlet used to divert runoff to a tank also are shown

Four of the tanks filled to capacity and/or overflowed during a few of the initial precipitation events. Consequently, splitters (manufactured by Oasis Design[1]) were installed on July 14–15, 2009 between the outflow of the flumes and the inlet of the collection tanks. The splitters were placed on concrete bases and leveled. Each splitter then was calibrated to determine the percentage of water transmitted through the tank using a known inflow volume. Splitters were recalibrated in the spring of 2010 following the final snowmelt to account for any changes that may have resulted from freeze-thaw effects on the splitters or their concrete bases. The initial calibration values were applied to all samples collected prior to January 23, 2010, and the recalibration values were applied to all subsequent samples. This date was selected as the cutoff because prior to January 23 there was minimal freezing, whereas a snowpack and below-freezing temperatures persisted throughout most of the remaining winter.

Immediately prior to and during sample collection, the contents of the tank were stirred with a long-handled brush to re-suspend settled solids and the interior sides and bottoms of the tanks were brushed to remove adhered sediment. Three replicate samples of approximately 1-L volume were collected from each tank, and

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the US Department of Agriculture of any product or service.

the order of the samples was noted in case sediment concentrations were found to be highest in the first sample. This situation had been observed in a prior study when large slugs of sediment were present in the pipe between the tank and the valve that were not or could not be re-suspended during stirring (Holz 2009). However, based upon the replicate sample concentrations, this behavior was not observed in the current study. Solids that were present in the flumes were considered to have been discharged from the waterbar during the associated storm event or series of events, so those solids also were collected and placed into small labeled plastic bags for inclusion in the total sediment yields for the corresponding sample and collection date. Following collection of the samples, the tanks were emptied. Stirring continued while the tank was emptying to eliminate sediment carryover into the next collection period.

Sediment concentrations were determined for each of the three subsamples from each tank at the US Forest Service's Northern Research Station office in Parsons, WV. Standard Method 209 C, involving vacuum filtration, was used to determine the sediment concentrations (APHA et al. 1985). However, samples collected soon after pipeline installation contained large sediment masses that were impossible to filter efficiently. Consequently, most of the samples collected through November 2009 were centrifuged to separate most of the solids from the water prior to filtering the remaining supernatant.

Total sediment mass was determined after combustion at 550 °C to remove organic material from the solids derived from centrifuging and filtering (Standard Method 209 D; APHA et al. 1985). Using the total sediment and volume of water in each sample bottle (determined gravimetrically), the sediment concentration (mg L^{-1}) for each subsample was calculated. The total volume in each tank per collection period was applied to the volume-weighted mean sediment concentration of the three subsamples to calculate total sediment loads (kg) per collection period for each study segment.

Percent vegetative cover on the pipeline corridor segments was determined using digital photography at the end of the first growing season (approximately 3 months after seeding). Photographs were taken on days with no precipitation between July 28 and August 14, 2009. The process is described briefly here but greater detail is given in Harrison (2011). The procedures generally follow those in Bold et al. (2010).

The outside boundary of each pipeline corridor segment was marked with a rope, and a rectangular frame constructed of PVC pipe was used to define the boundaries of a variable number of photographed subsections within each segment. The photographs were taken with a Canon™ Power Shot G2 4.0 megapixel camera mounted on a swivel bracket on a prism pole positioned at an angle approximately parallel to the slope of each segment subsection. The ArcGIS™ software was used to determine the area delineated by the frame and/or rope boundaries for each subsection and calculate scale factors between photographs within a corridor segment. The Erdas Imagine™ software was used to classify the photographs as "vegetation" or "other" for percent vegetation cover calculations.

Statistical comparisons were made using the SAS software (SAS Institute 1998). Sediment concentration, loading, and runoff volume comparisons were made using repeated measures with one-way analysis of variance (ANOVA). Concentrations are compared statistically as least square means, while total values are used in comparisons of loadings and runoff volumes. Measurements of vegetative cover were made only one time in each pipeline segment, so the Tukey's studentized range test was used to determine statistical differences after ensuring assumptions of normality were met using the Shapiro-Wilk test ($\alpha = 0.05$). All statistical comparisons were considered significant at $p \leq 0.05$.

3 Results

3.1 Soil Loss

Sediment concentrations for all of the waterbar segments were highest during the first growing season (Fig. 4) which immediately followed the completion of ROW seeding and mulching. During that time period, the northwest-facing segments generally reached higher concentrations, and a greater number of collection periods had higher concentrations than the opposing southeast-facing segments. Segments for which there was no runoff present in the tanks at the time of sample collection generally were associated with the southeast-facing segments. All southeast-facing segments except segment 13 had at least one collection period that yielded insufficient runoff to obtain a sample for laboratory analyses, and most had at least 3 collection periods with no sample volume. By comparison,

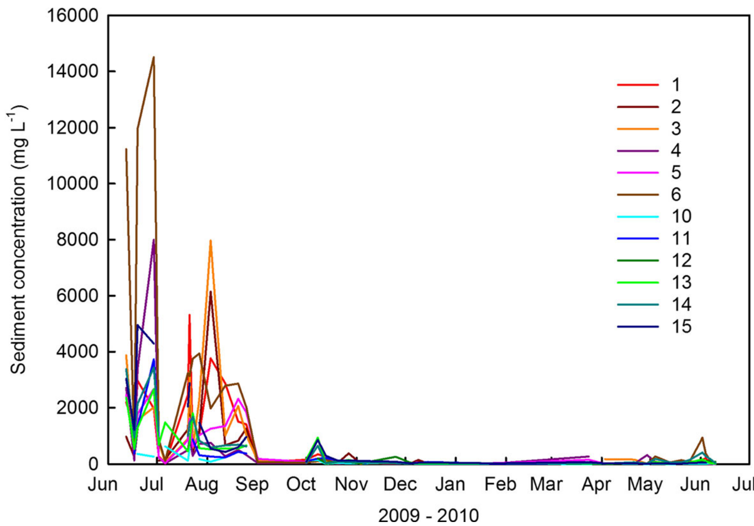

Fig. 4 Sediment concentrations (mg L^{-1}) across the year of study from each of the 12 pipeline segments

northwest-facing segments 2, 3, and 4 each had only a single collection period with no runoff during the first 3 months.

Sediment concentrations were by far the greatest from segment 6. The concentrations exceeded 10,000 mg L^{-1} in three collection periods, whereas the highest concentration from any other segment during the first 3 months was 7994 mg L^{-1}. Including segment 6 in the calculation, the mean concentration for samples collected from the northwest-facing segments from June through August 2009 was 2080 mg L^{-1}, which was significantly higher (p = 0.0027) than the mean of 1107 mg L^{-1} for same period for the southeast-facing segments. Excluding segment 6 reduced the mean from the northwest-facing segments by about 25% to 1590 mg L^{-1} for that 3-month period, which was still significantly greater than from the southwest-facing segments (p = 0.0494), though marginally so.

After August 2009, concentrations from all pipeline corridor segments fell to much lower concentrations. Average concentrations during the last 9 months of study were not significantly different (p = 0.74) between the six northwest-facing segments ($\bar{X}$ = 71.3 mg L^{-1}) and the six southeast-facing segments ($\bar{X}$ = 76.0 mg L^{-1}). The variability in concentrations among sample collection periods and among segments within individual sample collection periods also was much smaller after August (Fig. 4).

Total sediment yields, or loads, for the year from the individual segments ranged from 2.6 kg ha^{-1} $year^{-1}$ (segment 12) to just over 1400 kg ha^{-1} $year^{-1}$ (segment 6) (Table 4), illustrating the tremendous variability in erosion potential that exists among pipeline corridor segments that are in relatively close proximity and have similar physical characteristics. Sediment loads were poorly correlated with physical ROW characteristics, so factors such as slope and hillslope length that typically influence erosion losses (Holz et al. 2015) were not important in explaining the wide variation in soil losses. The lack of correlation probably resulted from the small range in each of the physical characteristics among the 12 study segments (Table 2).

Like concentrations, most of the sediment load from both aspects was lost during the first 3 months (Table 4). That sediment yields were less during the last 9 months than the first 3 months of the study is somewhat remarkable given that sediment yields are the product of concentration and runoff. Total yields were expected to be greater during the 9-month period because the greater duration of the latter period (9 vs. 3 months) resulted in more sample collection periods (24 vs. 14) and, more importantly, greater total runoff (Table 5). However, even though the first growing season was one third the duration of and total runoff during that growing season was less than the subsequent 9 months, the concentrations were so high during the first 3 months that they dominated the loading calculations.

On the southeast-facing segments, total sediment losses during the first growing season tended to be about an order of magnitude greater than during the subsequent 9 months (Table 4). By comparison, total sediment losses during the first growing season on the northwest-facing segments were one to two orders of magnitude greater than the last 9 months. Overall total sediment yields were much greater from northwest-

Table 4 Sediment yields (kg ha^{-1}) from each pipeline segment for the first growing season, the next 9 months, and over the entire 12-month study

NW-facing segment	Time period			Paired SE-facing segment	Time period		
	June 2009–Aug. 2009	Sept. 2009–June 2010	June 2009–June 2010		June 2009–Aug. 2009	Sept. 2009–June 2010	June 2009–June 2010
1	367.9	6.2	374.1	10	3.6	0.5	4.1
2	362.5	8.9	371.4	13	43.1	5.9	49.0
3	1098.5	19.6	1118.1	11	4.0	1.5	5.5
4	581.9	13.8	595.7	15	90.7	4.4	95.1
5	112.7	11.8	124.5	14	62.3	10.3	72.7
6	1348.9	51.4	1400.4	12	2.2	0.4	2.6

Table 5 Total volume of runoff (in L) measured in tanks for the first growing season, the next 9 months, and over the entire 12-month study

NW-facing segment	Time period			Paired SE-facing segment	Time period		
	June 2009–Aug. 2009	Sept. 2009–June 2010	June 2009–June 2010		June 2009–Aug. 2009	Sept. 2009–June 2010	June 2009–June 2010
1	442	1051	1493	10	192	793	986
2	1135	1243	2379	13	405	522	927
3	3518	3481	6999	11	136	484	619
4	3370	4583	7954	15	172	429	602
5	248	1046	1293	14	188	997	1185
6	2700	3890	6590	12	11	194	205
Total	11,413	15,294	26,708	Total	1104	3419	4524

facing pipeline segments than those on the opposing hillside (Table 4).

Runoff volumes were important in explaining the differences in soil losses between aspects. Segments 1 and 5 (northwest-facing) had total 12-month runoff volumes that were similar to their respective southeast-facing paired segments, 10 and 14, but total runoff volumes from the other northwest-facing segments were 2.5 to 32 times greater than from the corresponding southeast-facing paired segments (Table 5). Therefore, not surprisingly, runoff from the northwest-facing segments was statistically greater ($p < 0.0001$) than from the southeast-facing segments. Although there was some seasonal cessation of runoff during winter when snowmelt did not occur, runoff did not undergo large declines from the first 3 months to the last nine (Table 5); consequently, declines in soil losses experienced during the last 9 months of study were due to decreases in sediment concentrations.

As a result of the importance that sediment concentrations played during the first 3 months, the role of seed rates on sediment loss is examined using sediment concentration data. Sediment concentrations were not significantly different between seed rates. This result holds for the overall comparison of the 1× seed rate to the 3× seed rate ($p = 0.0878$), as well as seed rate comparisons within aspects (NW-facing $p = 0.2097$; SE-facing $p = 0.5361$; Table 6). Restricting the comparison to the first growing season (i.e., the first 3 months of the study) to examine the effects of potential differences in initial seed catch also did not show differences in sediment losses between the 1× and 3× seed rate segments (Table 6). Likewise, excluding the first 3 months of the study to restrict the comparison of seed rates to the period after which vegetation was established (see next section), did not indicate significant differences in soil losses between the seed rates (Table 6).

3.2 Seed Rate Effects on Vegetative Ground Cover

No vegetative cover was present on the pipeline corridor immediately following construction near the start of the growing season, but cover became fairly dense within 2 to 3 months. Mean vegetative cover measurements in late July/early August 2009 for the 12 pipeline segments ranged from 55.2 to 79.0% (Table 7). Vegetative cover was not significantly different ($p = 0.1903$) between pipeline corridor segments seeded at the 3× rate ($\bar{X} = 66.1\%$, SE = 5.9) and those that received the conventional 1× rate ($\bar{X} = 54.4\%$, SE = 5.8) required by the MNF for pipeline ROWs. However, the 3× seed rate did have more-rapid initial seed establishment. The 3× seed segments could be visibly distinguished from

Table 6 Pairwise statistical comparisons of least square mean sediment concentrations (mg L^{-1}) from the pipeline segments during the first growing season following seeding (June 2009–Aug. 2009), during the subsequent 9 months (Sept. 2009–June 2010), and during the entire 12 months of study (June 2009–June 2010)

Comparison	June 2009–Aug. 2009		Sept. 2009–June 2010		June 2009–June 2010	
	Sediment concentration	Std. error	Sediment concentration	Std. error	Sediment concentration	Std. error
Seed rate						
1× seed rate	1318.00	240.87	67.32	9.14	539.70	78.97
3× seed rate	1923.33	251.17	80.45	9.17	751.52	80.40
p value	0.1095		0.3302		0.0878	
Northwest-facing						
1× seed rate	1744.02	382.69	67.88	12.37	687.99	133.01
3× seed rate	2514.49	387.46	74.77	12.37	969.11	133.68
p value	0.2271		0.7122		0.2097	
Southeast-facing						
1× seed rate	925.30	319.22	66.38	12.87	399.88	90.20
3× seed rate	1161.18	333.35	86.03	12.96	484.17	92.02
p value	0.6312		0.3378		0.5361	

Table 7 Paired statistical comparisons of percent vegetative cover measured on pipeline segments near the end of the first growing season (approximately the first 3 months of study) following seeding

Percent vegetative cover (top number) and standard error (bottom number)								Probability of difference between comparisons in row
Northwest-facing			Southeast-facing			All 1× segments	All 3× segments	
1×	3×	All	1×	3×	All			
53.6 2.9			55.2 12.7					0.9098
	53.2 1.0			79.0 2.8				0.0010
						54.4 5.8	66.1 5.9	0.1903
53.6 2.9	53.2 1.0							0.8928
			55.2 12.7	79.0 2.8				0.1414
		53.4 1.4			67.1 7.9			0.1179

the 1× seed segments in under 2 weeks from the time of initial seeding simply from the presence and density of grass shoots—this difference was evident even before the mulch application was completed (Fig. 5).

4 Discussion

The concentration data clearly indicate that erosion and soil loss from the pipeline ROW occurred even though a heavy application of straw mulch (Fig. 6) was in place on all the study segments at the time the first runoff samples were collected for this study. However, there was a period of time between trench backfilling/physical restoration of the ROW and mulching during which raindrop impact would have occurred on the pipeline corridor surface; consequently, soil particle detachment and some surface sealing from raindrop impact processes (which contributes to the creation of overland flow by reducing infiltration rates) (Meyer and Mannering 1963; Young and Wiersma 1973; Lattanzi et al. 1974; Elwell and Stocking 1976; Moss 1991; Quinton et al. 1997; Bhatt and Khera 2006) would have developed on the corridor surface prior to mulch application.

The primary purpose of the mulch treatment, once applied, was to provide erosion control by diminishing

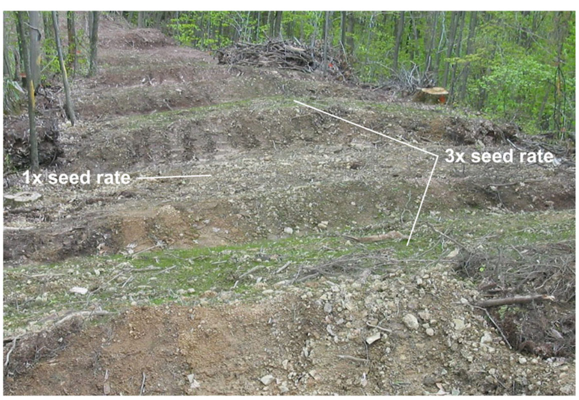

Fig. 5 Vegetation became established more quickly on the pipeline segments seeded at the 3× rate than on segments seeded at the 1× rate. Growth began even before mulching was completed (photograph taken May 8, 2009)

Fig. 6 A relatively heavy layer of whole mulch (i.e., not chopped or hydromulched) was applied to the pipeline ROW after seeding and fertilizing

future raindrop impact, associated soil particle detachment, and subsequent soil surface sealing. It is not possible to quantify the effectiveness of the straw mulch in controlling raindrop impact in this study, but it was applied more heavily than the authors have observed previously at many other locations of soil disturbance (e.g., forest road cutbanks and fillslopes). Straw mulch has been shown to be effective at reducing raindrop impact in other studies (Döring et al. 2005), but it does not eliminate erosion entirely (e.g., Meyer et al. 1972; Lattanzi et al. 1974; Jennings and Jarrett 1985), so some additional erosion undoubtedly occurred while the mulch was in place. Consequently, mobilization of soil particles detached during the pre-mulch period and soil detached post-mulching combined with the longer-term effects of initial soil sealing on sediment transport likely contributed to the high sediment concentrations early in the study, particularly during the first several collection periods in June 2009.

Re-emergent flow (from the subsoil) and saturation excess overland flow (Dunne and Black 1970) that do not depend on raindrop impact or surface sealing also may have contributed to the high sediment losses during the first growing season. Both mechanisms would allow runoff to develop on the soil surface and further detach and transport soil particles.

Re-emergent flow could result from the design of the waterbars used for drainage on the pipeline corridor. As is typical for waterbar construction, the bottom of each waterbar is below the grade of the ROW surface since this construction maximizes the potential for containing drainage within the waterbar. Due to the flashy hydrologic responses of streams in this area (Swistock et al. 1997), a substantial portion of non-vertical subsurface flow (also known as interflow or throughflow) on steep slopes is believed to occur in this area, perhaps either along the soil/parent material interface (which is encountered from <1 to 2 m below the surface) or along the organic layer/mineral soil interface, both of which have been theorized for flashy responses (e.g., see Hewlett and Troendle 1975; McDonnell et al. 1991; Brown et al. 1999). Regardless of the depth that subsurface flow predominantly occurs, it is an important hydrologic component at relatively shallow depths. As such, soil water flowing at depths at and above the base of a waterbar could be captured by it and be discharged from the corridor as re-emergent flow. In this situation, the principal sources of elevated sediment presumably would be the bases and reverse-grade faces of the waterbars.

Soil characteristics on the northwest-facing hillside may have increased the opportunity for waterbar interception of subsurface flow. The soil description for soil pit 1 (i.e., location 1, Appendix 0) on the northwest-facing hillside noted a layer containing peds with clay skins (i.e., soil aggregates with a thin clay coating) beginning at 50-cm depth (i.e., in the Bt layer); a similar layer was not present on the southeast-facing slope (i.e., location 3, Appendix 0). The clay-skinned ped limited percolation, as noted by the presence of wet conditions in and immediately above the Bt layer (though redox was not noted in the soil description). The limitation of vertical drainage would have encouraged drainage to occur primarily along the layer. The pipeline itself was installed below the depth of the drainage-limiting layer, but the trench in which it was buried was essentially only the width of the bucket on the excavator—that is, the entire width of the disturbed surface of the ROW was not excavated. Thus, even with the construction activities, much of the drainage-limiting layer probably would not have been disturbed or destroyed by the pipeline installation. Since the clay-skinned particles were found beginning at 50 cm below the soil surface, it is conceivable that the waterbars intercept subsurface flow that moves along and above that layer.

The presence of the limiting layer also provides the opportunity for incomplete infiltration and saturation excess overland flow when soil above the limiting layer is near or at saturation (in this situation the first scenario also could be occurring). Pierre et al. (2015) noted that an impermeable soil layer occurring at a depth of <50 cm in pipeline corridors in the Eagle Ford Shale play in Texas created a high potential for surface runoff. Sheet (interill) erosion or rill erosion by overland flow would be possible in the presence of the relatively thick layer of straw mulch. Long pieces of whole, unchopped straw (as used in this study) tend to bridge across high points on the ground, and as a result they do not fill in spaces or form a mat on the soil surface (Meyer et al. 1972; Foltz and Dooley 2003; Döring et al. 2005) that can protect the soil from the erosive energy of surface flow. If overland flow developed, both sheet and rill erosion probably occurred but sediment production from rills appears to have been primarily from small, poorly developed rills as there was no visible evidence of extensive rill development on any of the pipeline study segments.

Based on runoff volumes, the northwest-facing pipeline segments most influenced by the drainage-limiting layer were probably segments 3, 4, and 6. These three segments had much greater runoff volumes than segments 1, 2, and 5 (Table 5). The inconsistency in runoff among the six adjacent segments suggests that if the layer containing clay skins is affecting runoff processes, the layer is not continuous across all segments. A second soil pit on the northwest-facing hillside and just downslope from pipeline segment 6 did not contain clay skins or other drainage limitations (i.e., location 2, Appendix 0), which may be evidence that the layer is fragmented.

Temporal sediment concentration behavior suggests that vegetation establishment was largely responsible for limiting the duration of the high soil losses to the first 3 months of the study. Vegetative cover at the end of the first growing season was within the range of 50 to 70% cover reported in the literature needed to substantially reduce erosion (Quinton et al. 1997; Carroll et al. 2000). Exponential declines in sediment concentrations and soil losses have been observed in other studies with increasing vegetative cover (Bethlahmy and Kidd 1966; Orr 1970; Dyrness 1975; Quinton et al. 1997; Megahan et al. 2001; Moreno-de las Heras et al. 2009; Wade 2010). The growth of grasses and herbaceous plants presumably provided both root development to stabilize soils and roughness from aboveground stems (Bhatt and Khera 2006; Gray 1995; Woo et al. 1997) that reduced the erosive energy of surface flow (on the ROW surface and within the waterbars) in a way that the unchopped straw mulch could not. In addition, dense accumulations of litter and organic matter developed within the waterbars by the end of the first fall season and remained there through the end of the study. These litter packs would have provided additional protection against erosion within the waterbars.

Given the lack of erosion-control benefits from tripling the seed rate, this study provides little support for the increased costs involved in procuring more seed, particularly native seeds that can be quite expensive. Costs of the individual species at the time they were procured and applied are not available, but the total 2013 price for the 1× application rate for these species from the same nursery was \$527.52 per ha, making the 3× seed cost nearly \$1600 per ha of pipeline right-of-way (~\$475 per km of the 9-m-wide pipeline right-of-way). Even if greater erosion control had been observed with the higher seed rate, the increased cost may be viewed as unacceptable compared to the benefit received. However, while broad-scale use of higher seeding rates may be cost prohibitive, there could be specific locations or situations where higher seed rates are desirable. For example, a quicker seed catch may be deemed important in sensitive soils or landscapes or from an esthetic perspective where ground disturbance is highly visible to the public.

The temporal responses in sediment concentrations illustrate that the period most critical for erosion control on a pipeline corridor is the time prior to vegetation establishment (i.e., at least 50% cover). Consequently, other techniques are essential for controlling soil losses and sediment transport during this period. Chopped mulch may provide better contact with the soil surface and greater roughness to reduce erosion during that period; however, chopped mulch is chopped and applied using mechanical means, which is typically not possible or economical in many remote settings.

Other options for erosion control within the first months of pipeline completion are application of materials that bind to the surface and provide soil protection through chemical or physical processes. These types of materials include soil conditioners, such as polyacrylamides (PAMs), gypsum, or gypsiferous materials (Edwards et al. 2016), and hydromulch composed of a bonded fiber matrix or flexible growth media (Nelson 2006; McLaughlin and Jennings 2007; Nelson 2012). Soil conditioners improve soil stability (Shainberg et al. 1990; Agassi and Ben-Hur 1991, 1992; Chaudhari and Flanagan 1998) and protect the soil surface against sealing and erosion sediment transport (Yu et al. 2003). Conditioners could be used in combination with more traditional mulch materials (e.g., straw) to protect the surface from raindrop impact. Bonded fiber hydromulches or flexible growth media results in a thicker layer of organic material or organic plus biodegradable synthetic material that reduces erosion (McLaughlin and Jennings 2007; Nelson

2012; Texas Department of Transportation 2014) by chemically binding to the soil surface and flocculating soil particles to protect against raindrop impact and overland flow and sediment transport. Soil conditioners can be applied as spray treatments with hand sprayers (Petersen et al. 2007) or dry applications on wet or moist soils (Wallace and Wallace 1986), so they could be used even on ROW sections that are inaccessible to vehicular traffic or mechanical equipment. Bonded fiber matrices and flexible growth media are applied using hydraulic spraying, so access is required, but this is not typically a problem since access is provided for heavy equipment for pipeline installation.

Soil conditioners have been shown to work well at reducing erosion and soil transport on construction sites (Sojka and Lentz 1994, 1996a, 1996b), including on steep slopes, though the required application rates are somewhat greater than on flatter ground (Green and Stott 2001). Soil conditioners have been shown to be effective for controlling soil losses in a wide range of climates, from humid to arid (Roose 1975; Green and Stott 2001), and for as long as 6 to 10 weeks (Fox and Bryan 1992; Petersen et al. 2007). However, they tend to work best with soils that have moderate to high clay contents (Trout and Ajwa 2001; Davidson et al. 2009), but the effectiveness of PAMs can be improved on some coarse textured soils by using formulations with higher molecular weights (Levy and Agassi 1995; Green et al. 2000). Bonded fiber hydromulches and flexible growth media do not have limitations with the types of soils on which they can be applied so they provide options in situations that are not as well suited for soil conditioners, such as coarse-textured soils like sandy loams (e.g., Trout and Ajwa 2001; Ajwa and Trout 2006). They have been shown to be more effective than many other more commonly used soil cover products (McLaughlin and Jennings 2007), and like soil conditioners, they can be applied in combination with seed and other soil amendments (Nelson 2006, 2012) to promote fast vegetation establishment. Their long life prior to decomposition (6 to 12 months) allows additional seed applications to their surfaces if initial sowing is slow to reach required density.

Application costs for many soil conditioners are quite competitive with more commonly employed erosion control products. For example, the per hectare cost of PAM application was less than that of straw mulch application (i.e., the total product + application costs for each) (Flanagan and Chaudhari 1999). Bonded fiber hydromulches and flexible growth media are more expensive than many traditional soil cover BMPs, but they are beginning to be used on pipeline corridors in the central Appalachians and surrounding areas. Given that restoration constitutes only a small percentage of the costs of the development of energy transmission ROWs and the high profit margins of the industry, any of these products are affordable for restoration.

There are very few other studies of erosion from newly constructed pipeline corridors against which to compare our results. Most of the available studies concerning soil losses from pipelines are focused specifically on stream crossings (e.g., Blais and Simpson 1997; Reid and Anderson 1999, 2000; Reid et al. 2002; Lévesque and Dubé 2007; Castro et al. 2015) because these areas are most likely to affect water quality. However, while waterbody crossings may be among the most high risk areas in terms of water quality impacts, pipeline construction away from crossings is of substantial concern as this length typically comprises most of the pipeline corridor length and downslope sediment movement and transport can be quite long on steep slopes, especially when associated with concentrated flow from surface drainage features (Ketcheson and Megahan 1996; Wemple et al. 1996; Croke and Mockler 2001).

Estimates of erosion from the whole of pipeline corridors have come primarily from modeling efforts (e.g., Hann and Morgan 2006; Winning and Hann 2014). We could find only one other study by Holz (2009) of field-measured erosion rates from a pipeline corridor not focused on waterbody crossings. Holz (2009) measured sediment yields in discharge from four waterbars along a pipeline buried in a retired forest skid road in north central West Virginia. The sediment yields he reported were for a 10-month period, and they are in or above the upper range of our findings (Table 4), with total yields from his four monitored segments of 500, 600, 1100, and 1800 kg ha^{-1}. The annual first year losses from several of our corridor segments (Table 4) approximately equaled or were less than typical annual soil losses reported from well-managed forests in this region (112 to 224 kg ha^{-1} year^{-1}), which are considered to be quite low compared to other land uses (Patric 1976).

Sediment losses from pipeline corridor segments in the current study were small in comparison to losses from forest road corridors in this region, even though roads tend to be much less steep (≤10% grade) than cross-country pipeline corridors. For example, Kochenderfer and Helvey (1987) reported first year sediment losses on a newly constructed forest haul road on the FEF closed to general use (i.e., opened only for maintenance and sample collection for the sediment study) that were often one or more orders of magnitude higher than those from the pipeline corridor. The average sediment yield from three replicate ungraveled sections of 10% grade was approximately 84,064 kg ha^{-1} year^{-1}. From three replicate sections that were 12% grade and surfaced with clean gravel, the average sediment loss was approximately 8743 kg ha^{-1} year^{-1}, and from three sections that were 10% grade and surfaced with crusher run gravel, the average loss was 13,450 kg ha^{-1} year^{-1}.

5 Conclusion

Erosion was measured from 12 segments on a cross-country natural gas pipeline corridor on the Fernow Experimental Forest of the Monongahela National Forest, in north central West Virginia, USA. Segments were defined as the area between adjacent waterbars, which were used to control runoff on the right-of-way. Half of the corridor segments were on a northwest-facing hillside and the other half were on the opposing southeast-facing hillside. Seeds of seven native herbaceous and grass species were applied to the entire pipeline corridor. The rates of each species were those used by the national forest on all pipeline ROWs (1×). In addition, on three of the segments on each aspect, the seed rate was increased to equate to three times (3×) the normal application rate for each species.

Sediment concentrations originating from all the segments were highest at the beginning of the study, just after pipeline completion and seed, fertilizer, lime, and mulch application in late spring 2009. Concentrations declined exponentially during the first growing season (approximately the first 3 months of study). Sediment yields followed the same pattern. Much of the initial soil loss is believed to be from raindrop impact prior to the mulch application which created a source of detached soil that remained available for transport even after the mulch was applied. Re-emergence of subsurface flow and excess saturation overland flow also may have contributed to runoff and erosion in some northwest-facing segments, due to the presence of a drainage-limiting layer ~50 cm below the soil surface. Right-of-way revegetation is believed to be a primary reason for the decline in erosion observed by the end of the first growing season.

Vegetative ground cover on both aspects at the end of the first growing season exceeded the 50% level reported in the literature needed to reduce erosion losses. Pipeline segments receiving the heavier seed application had visible vegetation establishment on both aspects sooner than those with the lighter application, but sediment yields were not significantly different between the two seed rates. Therefore, the increased cost of the 3× seed rate does not appear to be justified by erosion control; however, heavier seeding may be warranted where quick cover is needed, such as locations where esthetics are important or in sensitive environments.

Annual sediment yields were generally less than or similar to those reported from another pipeline study in this region. Sediment yields also were much less than those measured from road corridors on the FEF that were much less steep than this pipeline corridor. The ROW was most susceptible to erosion losses prior to revegetation even though there was a relatively heavy layer of straw mulch applied to the right-of-way surface. Therefore, additional best management practices to control erosion during this period are warranted. The application of a soil conditioner, flexible growth medium, or bonded fiber matrix in combination with traditional soil amendments and seed mixtures may be an effective strategy for improving erosion control during the critical ROW restoration period when vegetation has not yet become established.

Acknowledgments The authors thank the USDA Forest Service, Monongahela National Forest, who provided funding and assistance for this administrative study. We particularly thank Linda Tracy, Forest Geologist (retired) for her assistance with logistics and Stephanie Connolly, Forest Soil Scientist, for describing the soils on the pipeline right-of-way. Also, thanks go to Greg Evans for his contributions to equipment installation and maintenance, sample collection, and laboratory analyses, and Frederica Wood for surveying, ground cover photography, and image analysis.

Descriptions of soil pits 1-3 adjacent to the FEF pipeline ROW, made by Stephanie J. Connolly, Monongahela National Forest Soil Scientist. Depth units for all three pits are cm. Blank fields indicate data that were not recorded at the time the soil was described.

Soil Type: Shouns

Area: Pipeline Erosion Study, Location 1, Northwest-facing side	Date: 6/3/2010	Stop No:
Classification:		
Location: Fernow Experimental Forest		
N. veg. (or crop): Hardwood: Red Oak, Greenbrier	Climate: Mesic	
Parent Material: Colluvium over residuum (Hampshire residuum: siltstones and sandstones)		
Physiography: Allegheny Mountains		
Relief: Backslope	Drainage: Moderately Well Drained	Salt or alkali:
Elevation:	Gr. Water:	Stoniness:
Slope:	Moisture:	
Aspect:	Root distrib:	% Clay:
Erosion:	% Coarse Fragments:	% Coarser than V.F.S.:
Permeability:		
Additional Notes: Bt is wet, water is moving through profile. The Bt is not argillic horizon but clay films are present.		

Horizon	Depth	Color (Moist)	Texture	Structure	Consistence (Moist)	Reaction	Boundary	Roots	Clay Films	Rocks
Oe/Oa	0-3									
A	3-8	7.5 YR 3/2	SIL	2, F, GR	VFR		CW	3 VF, 3 F		10% GR
BA	8-17	7.5 YR 3/4	SIL	1, M, SBK → 2, F, GR	VFR		CS	3 FC, 1 VFM,		10% GR
Bw	17-50	7.5 YR 4/4	SICL	2, M, SBK	FR		CS	1 F, 1VF, 2M		20% GR
Bt	50-80	7.5 YR 4/4	SICL	2, M, SBK → 2, F, SBK	FI		CS	2 F	f, F, D, TF, RF, CLF	40% GR, 25% CN, 25% FL
BC1	80-108	Boulder decomposing in place								
BC2	108-125	7.5 YR 3/4	SIC	0, MA	VFI		CS			30% GR
Cr	125	Green siltstone								

Soil Type: Calvin		
Area: Pipeline Erosion Study, Location 2, Northwest-facing side	Date: 6/8/2010	Stop No:
Classification:		
Location: Fernow Experimental Forest		
N. veg. (or crop): Northern Red Oak, Red Maple, Sugar Maple, Beech		Climate: Mesic
Parent Material: Hampshire residuum		
Physiography: Allegheny Mountains		
Relief: Bench	Drainage: Well Drained	Salt or alkali:
Elevation:	Gr. Water:	Stoniness < 0.1 %
Slope: 10%	Moisture	
Aspect: 298° W	Root distrib.	% Clay
Erosion:	% Coarse Fragments	% Coarser than V.F.S.
Permeability:		
Additional Notes:		

Horizon	Depth	Color (Moist)	Texture	Structure	Consistence (Moist)	Reaction	Boundary	Roots	Clay Films	Rocks
Oi	0-3	Hardwood leaf litter								
Oe	3-6									
Oa	6-11									
A	11-17	7.5 YR 3/1	SIL	2, F, GR	VFR		CW	3 VF, 3 F		15% GR 5% FL
BA	17-34	7.5 YR 3/4	SIL	1, M, SBK → 2, F, GR	FR		CS	3 FC, 1 VFM,		5% GR 10% CN 10% FL
Bt	34-47	7.5 YR 3/4	L	2, M, SBK	FR		CS	1 F, 1VF, 2M	f, D, F, PF and RF	30% FL 30% CN
BC	47-57	7.5 YR 4/4	L	2, M, SBK	FR		CS	2 F		80% FL
C	57-79	5 YR 4/4	L	0, MA	VFI		CS	1 F		
Cr	79+	Decomposing shale								

Soil Type: Calvin		
Area: Pipeline Erosion Study, Location 3, Southeast-facing side	Date: 6/8/2010	Stop No:
Classification:		
Location: Fernow Experimental Forest		
N. veg. (or crop): Northern Red Oak, Red Maple, Sugar Maple, Beech		Climate: Mesic
Parent Material: Hampshire residuum		
Physiography: Allegheny Mountains		
Relief: Backslope	Drainage: Well Drained	Salt or alkali:
Elevation:	Gr. Water:	Stoniness: 1-3% FL
Slope: 65%	Moisture	
Aspect: S 60° E	Root distrib.	% Clay
Erosion:	% Coarse Fragments	% Coarser than V.F.S.
Permeability:		
Additional Notes: Pit to the left of the face of the pipeline. <30% rock in top 30 cm, increase in rock % 30-50% with depth; fractured bedrock; Bw2 has soil in pockets along rock fractures		

Horizon	Depth	Color (Moist)	Texture	Structure	Consistence (Moist)	Reaction	Boundary	Roots	Clay Films	Rocks
Oe	0-2						CS			
A	2-7	10 YR 3/3	SIL	1, F, GR	VFR		CW	2 VF, 3 F		15% GR 5% FL
BA	7-22	10 YR 4/4	SIL	1, M, SBK → 1, F, GR	FR		CW	3 FC, 2 VFM,		5% GR 10% CN 10% FL
Bw1	22-52	7.5 YR 4/3	L	2, M, SBK	FR		CS	1 F		30% FL 30% CN
Bw2	52-115	10 YR 5/4, 5 YR 4/3	L	1, M, SBK	FI		CS			80% FL
Cr	115+	Decomposing shale between harder rock, crumbles in hand.								

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