Non-point source pollution control using dryland vegetative filter strips
by Richard Allan Fasching

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science In Agronomy
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Abstract:
Dryland vegetative filter strips (VFS) have been used to control non-point source pollutants in several regions of the United States. Effectiveness of vegetative filter strips for removal of non-point source pollutants can be influenced by landscape, strip width, vegetative species, soil characteristics, and climatic conditions. Vegetative filter strips, as a resource conservation practice for control of sediment generated from cropland runoff, were studied. Simulated runoff, of the type associated with short duration, high intensity rainfall events, was applied to a Heldt silty clay loam (fine, smectitic, mesic Ustertic Haplocambids). Plots consisted of a 15-feet clean-tilled cropland source area and a 40-feet VFS located at the lower end of each plot, except for the control plot, which was devoid of growing vegetation. Six species of grass and two small grain crops were evaluated for their effectiveness in removing sediment. Grass species included pure strips of western wheatgrass (Pascopyron smithii), thickspike wheatgrass (Elymus lanceolatus ssp. Lanceolatus), pubescent wheatgrass (Elytrigia intermedium ssp. Barbulatum), intermediate wheatgrass (Elytrigia intermedium ssp. Intermedium), smooth bromegrass (Bromus inermis), and crested wheatgrass (Agropyron cristatum). Small grain crops analyzed were Amidon spring wheat and spring seeded Neeley winter wheat (Triticum aestivum L.). Using gated irrigation pipe, water was applied at the head of the clean-tilled source area to generate sediment-laden runoff which transported into the up-slope edge of each filter strip. Water applications simulated rainfall events equivalent to a 50-year 24-hour storm (wet soil profile) and a 100-year 24-hour storm (dry soil profile). Sediment-laden water was directed into the upper edge of each VFS until runoff occurred at the lower end of each strip. Water samples were collected from the lower end of each plot and analyzed for sediment content. Additionally, the rate of progression of water through each VFS was measured. Three simulations were evaluated, two under saturated soil profile conditions, and one under dry soil profile conditions. Results indicated that VFS are effective in reducing sediment concentration in runoff. For the wetted soil profile simulations, vegetative filter strips comprised of crested wheatgrass and smooth bromegrass allowed water to advance through the VFS an average of 272 sec and 263 sec, respectively, compared to the clean-tilled control plot which averaged 123 sec. Increase in duration that water stayed on the VFS modestly correlated with average sediment concentration of 5.5 g/L and 5.0 grams/L respectively, compared to the control plot which yielded 16.3 g/L of sediment. Under dry soil profile conditions sediment concentration in runoff from bromegrass and crested wheatgrass were averaged 9.5 g/L and 11.6 g/L, respectively, compared to 69.3 g/L from the clean-tilled control plot.

Water progression through the smooth bromegrass and crested wheatgrass VFS measured 257 sec and 263 sec, respectively, compared to a period of 80 sec for the water to progress through the clean-tilled fallow strip.

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APPROVAL

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Richard Allan Fasching

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Dryland vegetative filter strips (VFS) have been used to control non-point source pollutants in several regions of the United States. Effectiveness of vegetative filter strips for removal of non-point source pollutants can be influenced by landscape, strip width, vegetative species, soil characteristics, and climatic conditions. Vegetative filter strips, as a resource conservation practice for control of sediment generated from cropland runoff, were studied. Simulated runoff, of the type associated with short duration, high intensity rainfall events, was applied to a Heldt silty clay loam (fine, smectitic, mesic Ustertic Haplocambids). Plots consisted of a 15-feet clean-tilled cropland source area and a 40-feet VFS located at the lower end of each plot, except for the control plot, which was devoid of growing vegetation. Six species of grass and two small grain crops were evaluated for their effectiveness in removing sediment. Grass species included pure strips of western wheatgrass (*Pascopyron smithii*), thickspike wheatgrass (*Elymus lanceolatus ssp. Lanceolatus*), pubescent wheatgrass (*Elytrigia intermedium ssp. Barbulatum*), intermediate wheatgrass (*Elytrigia intermedium ssp. Intermedium*), smooth bromegrass (*Bromus inermis*), and crested wheatgrass (*Agropyron cristatum*). Small grain crops analyzed were Amidon spring wheat and spring seeded Neeley winter wheat (*Triticum aestivum L.*). Using gated irrigation pipe, water was applied at the head of the clean-tilled source area to generate sediment-laden runoff which transported into the up-slope edge of each filter strip. Water applications simulated rainfall events equivalent to a 50-year 24-hour storm (wet soil profile) and a 100-year 24-hour storm (dry soil profile). Sediment-laden water was directed into the upper edge of each VFS until runoff occurred at the lower end of each strip. Water samples were collected from the lower end of each plot and analyzed for sediment content. Additionally, the rate of progression of water through each VFS was measured. Three simulations were evaluated, two under saturated soil profile conditions, and one under dry soil profile conditions. Results indicated that VFS are effective in reducing sediment concentration in runoff. For the wetted soil profile simulations, vegetative filter strips comprised of crested wheatgrass and smooth bromegrass allowed water to advance through the VFS an average of 272 sec and 263 sec, respectively, compared to the clean-tilled control plot which averaged 123 sec. Increase in duration that water stayed on the VFS modestly correlated with average sediment concentration of 5.5 g/L and 5.0 grams/L respectively, compared to the control plot which yielded 16.3 g/L of sediment. Under dry soil profile conditions sediment concentration in runoff from bromegrass and crested wheatgrass were averaged 9.5 g/L and 11.6 g/L, respectively, compared to 69.3 g/L from the clean-tilled control plot. Water progression through the smooth bromegrass and crested wheatgrass VFS measured 257 sec and 263 sec, respectively, compared to a period of 80 sec for the water to progress through the clean-tilled fallow strip.

CHAPTER 1

INTRODUCTION

Contamination of water resources throughout the United States from agricultural related runoff has become an important environmental concern. Surface water runoff from tilled agricultural land can contain heavy loads of sediment and other non-point source pollutants including pesticides, nutrients, salts, toxic trace elements, and organic solids (Knapton, 1990).

Vegetated filter strips (VFS) located downslope from agricultural land have been shown to be an effective conservation practice for control of some non-point source pollutants, especially sediment (Magette et al., 1989; Dillaha et al., 1988). Vegetated filter strips are intended and designed to provide an area where sediment can be deposited before runoff reaches a stream, lake, or other body of water.

Vegetated filter strips are widths of planted or indigenous vegetation, usually composed of grasses and/or legumes or other dense vegetation located downslope of cropland, hayland, grazing land, forestland, or animal feedlot facilities, to provide erosion protection and filter nutrients, sediment, and other pollutants (Dillaha et al., 1989). Because of their relatively low implementation costs and reported effectiveness in removing non-point source pollutants, conservation and regulatory agencies and agricultural businesses are promoting VFS use. In 1997, the USDA Natural Resources

Conservation Service launched the National Buffer Initiative, which established a goal of "two million miles of conservation buffers in the U.S. by the year 2002." In the past, researchers have investigated effectiveness of VFS. However, most of these efforts have concentrated on sediment removal from strip mine runoff and nutrient and solids removal from feedlot runoff (Dillaha et al., 1989; Dillaha et al., 1988; Young et al., 1980; Magette et al., 1986). Because of lack of published research results and verified design criteria, VFS design, in general, is based upon experience and limited data. Implemented designs are often adapted from neighboring state and Federal agency standards.

Adequate research and verified design procedures are not available in every state. Consequently, a wide range of suggested VFS designs for reducing sediment and other non-point source pollutants can be found in current literature. Adoption of an inadequate design or installation in inappropriate areas could result in VFS failures.

Montana, and the Northern Great Plains region in general, is characterized by arid or semi-arid climatic conditions where crop available precipitation predominantly comes in the form of short duration, high intensity, rainfall in the spring and fall. These rainfall patterns occur when cropland is most susceptible to water erosion due to traditionally practiced clean-tilled seedbed preparation and high soil moisture conditions from over winter sub-soil recharge. Since the early 1900's, in an attempt to optimize low annual precipitation, producers in the Great Plains region have utilized a crop-fallow rotation (50% of acres cropped, 50% fallowed) where fallowed fields are traditionally kept weed free by conventional tillage techniques. Considering that the farm size in Montana averages over 1,100 acres, non-point source pollution from large parcels of land is of unique concern (USDA Agricultural Statistics, 1998). Even with the benefits USDA agricultural programs have provided for reducing erosion since 1985, there is still a risk of non-point source pollution. Montana has increased the use of soil protecting conservation practices including residue management and wind strip cropping over the years. However, there are still over 4 million acres of fallowed land annually, up to 50% of which may not be protected against erosion (National Crop Residue Management Survey, 1998). VFS have traditionally been designed, evaluated, and implemented for site-specific situations. In consideration of the uniqueness of agriculture in Montana and the Northern Great Plains, documented localized VFS design could aid conservationists and producers in effectively reducing sediment from agricultural lands.

Thesis Objective

This study evaluated effectiveness of various species of grass and two small grain crop VFS in removing sediment from runoff. The ultimate goal was to determine optimal dryland vegetative filter strip width and vegetative performance under climatic conditions typical of Montana agricultural lands and to provide improvements in VFS design procedures. To achieve this goal, plot studies were conducted using simulated rainfall and forced runoff techniques to investigate transport of sediment in VFS as influenced by vegetative species and filter strip length.

Water resources in Montana are of considerable value. Currently, Montana's water quality is some of the best in the United States, producing blue ribbon fishing opportunities, high quality irrigation water for crops and forages, livestock water, household water, sustenance for wildlife, and aesthetic values in unspoiled lakes and streams (Knapton, 1990). Montana has approximately 176,750 total miles of streams, of which about 30% are perennial streams. In addition, there are approximately 10,200 lakes comprising 845,000 acres. Consequent to farming and ranching, some water bodies have already been threatened by non-point source pollution, especially sediment, from runoff generated by water erosion from cropland, forage producing land, and grazing land (Montana DEQ, 1998).

The hypothesis to be tested was that certain vegetative species, in combination with design widths, could be effective in removal of sediment generated from cropland runoff. Examination of relationships from data collected in different experiments, and in conjunction with climate and other soil and vegetative variables, may produce a correlation adequate to provide an appropriate design procedure for installing effective VFS in Montana, particularly in association with dryland cropping systems involving tilled cropland.

Literature Review

Design Species

Vegetative filter strips have been shown to be an effective best management practice (BMP) for the control of some non-point source pollutants, especially sediment and sediment-bound contaminants (Dillaha et al., 1989). Prior to the mid-1980's much research with VFS focused on sediment removal from strip mining operations, nutrient and solids removal from feedlot runoff, and municipal wastewater treatment. Typically, research focused on physical design characteristics, such as length, slope, and hydraulic water flow, when analyzing VFS and their associations with non-point source pollutant reduction (Dillaha et al., 1989). In most of these studies a very limited number of grass species and crops were included in assessing effectiveness of VFS. Most reported findings were not linked to effectiveness of specific grass or crop species, but were attributed to associated factors of the VFS as a whole (i.e. reduction in hydraulic flow and infiltration) (Magette et al., 1989; Dillaha et al., 1989, 1988, 1987, 1985). More recently, grass and crop species and their individual performance in a VFS have been included in research analysis (Madison et al., 1992). However, species utilized for VFS investigations are not necessarily adapted to Montana dryland conditions where annual precipitation often averages only 12-14 inches (30-35 cm). In this thesis six species of grass and two small grain crops adapted to dryland conditions in Montana are reported and used in the analysis.

Infiltration

Infiltration can be an important removal mechanism for runoff, and which affects VFS performance, because many pollutants associated with surface runoff enter the soil profile in the vegetated areas. Infiltration is also important because it decreases surface runoff, which in turn reduces ability of runoff to transport pollutants (Dillaha et al., 1988). Because infiltration is relatively easy to quantify in regard to VFS effectiveness, many VFS have been designed to allow all runoff to infiltrate. This approach to the utilization of VFS requires large land parcels to completely remove pollutants. In an effort to remove variability in results of the evaluation of effectiveness of various grass and crop VFS, in this study the soil profile of the tested VFS was saturated just prior to sediment runoff generation for two experiments. In a third experiment, runoff was initiated under dry soil profile conditions.

Filter Strip Length

Effective length of filter strips in removing sediments from runoff water is not definitive. Young et al. (1980) reported that a 24m long cropped area removed as much as 92% of the sediment associated with feedlot runoff. Magette et al. (1986) found that required filter lengths for approximately 90-95% pollutant reductions in runoff ranged from 3m to lengths equivalent to the area up slope from the filter. If the latter criteria were followed in designing a VFS, a cropland field one acre in size would require a VFS one acre in size. Magette et al. (1986) concluded that effectiveness of VFS is highly dependent on condition of the filter itself and that removal of sediment predominantly occurred at the interface between the source area and the filter itself and is not necessarily a function of the filter length. Madison et al. (1992) compared effectiveness of three lengths of grass filter strips, 15, 30, and 45 feet, and reported that an average of 96% and 99% of the sediment was trapped in the 15 feet and 30 feet filter strips, respectively. There was no benefit in sediment trapping efficiency when the filter strip was lengthened to 45 feet. Runoff water tended to concentrate in small rivulets in the longest strip, which decreased infiltration, although sediment removal remained high.

Dillaha et al. (1988) analyzed two filter strip lengths, 4.6-m (15 ft) and 9.1-m (30 ft), in the removal of sediment from feedlots. The 9.1-m (30 ft) filters removed an average of 91% of the sediment generated while the shorter 4.6-m (15 ft) filters reduced sediment by an average of 81%. The most effective region for sediment removal was just up slope and in the first few meters of VFS. These observations are supported by the fact that doubling the filter strip length, from 4.6-m (15 ft) to 9.1-m (30 ft) resulted in only an additional 10% reduction in sediment removal. In a subsequent study of non-point source pollution control in 1989, Dillaha et al. found that doubling the length of filter strip from 4.6-m (15 ft) to 9.1-m (30 ft) resulted in reduced sediment yield by an additional 10-23%. Total reductions in sediment in runoff averaged 53-86% for the shorter strips to 70-98% for the longer strips.

The USDA NRCS design criteria for filter strips requires vegetation at least 6.1-m (20 ft) long for slopes of less than one percent (USDA NRCS, Field Office Technical Guide, Filter Strips, 1998). Widths proportionately longer are recommended for steeper slopes and/or for less permeable soils. The following table illustrates typical design requirements corresponding to slope:

Table 1. Minimum strip widths for VFS on sloping land.

Slope	Minimum Filter Strip Width	
0-3%	20 ft	6.1 m
4-9%	25 ft	7.6 m
10-15%	30 ft	9.1 m
15%+	40 ft	12.2 m

In an effort to quantify effects of VFS length and associated sediment reductions, experimental plots of various lengths were commonly established with methodologies to collect runoff water and sediment at the lower end of the plots (Dillaha et al., 1989; Madison et al., 1992). This thesis incorporates plots of various vegetative species composition and a single VFS length and attempts to quantify the effects of VFS length by recording rate of advance of the wetting front through the filter strip and concentration of sediment in runoff.

Precipitation Simulation

In previous research, rainfall simulators have been used to apply certain predetermined amounts of water that represented specific storm events. Dillaha et al. (1985, 1988, 1989) applied 50 mm/hour (2.0 in/hour) of water during all simulations. This amount represented an approximate 2 to 5 year recurrence interval, one hour duration in the state of Virginia. The nominal delivery rate of 48.25 mm/hour (1.9 in/hour), which also approximates a 2-5 year return period storm in the study area, was applied by Magette et al. (1986). Simulations in Kentucky applied amounts of water equivalent to a 10-year, 24 hour rainfall intensity, which equated to about 2.5 inches per hour (Madison et al., 1992).

The USDA NRCS national standard for filter strips requires width design based on a 2-year, 24 hour rainfall intensity. In Montana, a 2-year, 24 hour rainfall storm event equates to approximately 1.2 to 1.8 inches per hour, depending more precisely on the geographic location of the site (Miller et al., 1973).

<u>Water Quality Sampling</u>

Water quality samples from VFS studies have been collected primarily two ways; (1) randomly throughout the runoff event (Magette et al., 1989), or (2) at specified time intervals during the simulations, i.e. 3 minute intervals. (Dillaha et al.,1989; Dillaha et al., 1985). Water samples collected from vegetated and bare strips are typically preserved by freezing and analyzed for nutrients and sediment at a later date using methods outlined by the United States Environmental Protection Agency (Dillaha et al., 1985, 1988, 1989).

Sojka et al. (1992) utilized sediment settling volume in a graduated vessel (Imhoff Cone, supplied by Fisher Scientific*) to correlate total mass of suspended sediment collected from runoff with sediment concentrations. This method allowed suspended sediment to settle for an established period of time (0.5 hour). Results were then regressed against sediment concentration (total sediment, g L^{-1}). This technique provided a method of rapid and accurate suspended-sediment determination in the field. Sojka etal. (1992) suggested that, although general readings from the graduated cones were adequate for diagnostic purposes, individual field calibrations should be completed for research purposes.

* Supplier information is provided for reader information only and does not imply endorsement in any way.

CHAPTER 2

METHODS AND MATERIALS

Overview

The experiment was designed as a replicated, randomized complete block, with each block consisting of eight grassed VFS and a control fallow strip. Each block was replicated three times. The eight vegetative species consisted of western wheatgrass (*Pascopyron smithii*), thickspike wheatgrass (*Elymus lanceolatus ssp. Lanceolatus*), pubescent wheatgrass *(Elytrigia intermedium ssp. Barbulatum*), intermediate wheatgrass (*Elytrigia intermedium ssp. Intermedium*), smooth bromegrass (*Bromus inermis*), crested *wheatgrass (Agropyron cristatum*), Amidon spring wheat and Neeley winter wheat (*Triticum aestivum L.*).

In order to generate sediment from overland flow upslope of each VFS, a 20-feet wide sediment generation area, consisting of clean-tilled and fallowed ground, was established upslope of each VFS. Gated irrigation pipe was placed parallel to the upslope edge of the sediment generation area.

Just prior to runoff simulations, the soil profile of the VFS and the fallow source (sediment generation) area were wetted to soil water holding capacity. Water was applied to the source area to generate sediment-laden water that flowed over the VFS and distance of advance of the wetting front through the VFS was measured every ten seconds. Five runoff samples were collected manually from the toe slope position of each VFS, beginning with initial runoff at the base of each plot. Samples were each placed into Imhoff cones to determine sediment yield. Analysis was conducted for the determination of suspended sediment and water flow through the VFS.

Plot Design and Location

Studies were conducted during the summers of 1997 and 1998 on a Heldt silty clay loam soil (fine, smectitic, mesic Ustertic Haplocambids). The soil series consists of deep, moderately sloping, well-drained soils, formed in deep alluvium. In a representative soil profile the surface layer is grayish-brown silty clay loam about seven inches thick. The subsoil is grayish-brown silty clay loam eleven inches thick. The available water holding capacity is relatively high, approximately 5.5 inches in the top 30 inches, and permeability is slow. The soil is well suited for vegetative filter strips and its characteristics are representative of sites in Carbon county and the adjacent dryland farming area.

The study site is located at the USDA Plant Materials Center, Bridger, Montana, which is approximately 40 miles southwest of Billings, Montana. The site is approximately 2 acres with a consistent and uniform slope of four percent. The elevation is 3, 680 feet above sea level. Average annual precipitation is 13.6 inches with approximately 123 freeze-free days per year. The ten-year erosive energy factor (10-year EI) is 17. The EI factor is the measure of intensity of rainfall during the year (Revised

Universal Soil Loss Equation, ver. 1.06, 1998). For comparison, the EI value for Boise, Idaho is 12 and for Richmond, Virginia is 100. Primary erosive rainfall energy at the site occurs May through June, when seeded cropland is typically most vulnerable to water erosion due to most crops having not yet matured enough to provide protection to the soil surface.

Each plot had a clean-tilled cropland sediment source area directly upslope from a vegetated filter strip. The cropland source area upslope from each VFS was 20 feet long and 20 feet wide. Each VFS was 40 feet long and 20 feet wide. Eight vegetative species and a fallow control treatment (nine treatments) with three replications in a randomized complete block design were established. Figure 1 illustrates a single block of experimental plots. Vegetated filters included six grass species and two small grain crops adapted to the soil and climatic conditions of the site.

To prevent cross contamination between plots during simulated erosion events, a shallow furrow was excavated between plots that directed runoff water to the tailwater recovery ditch.

Grass species analyzed included pure strips of western wheatgrass, thickspike wheatgrass, pubescent wheatgrass, intermediate wheatgrass, smooth bromegrass, and crested wheatgrass. Small grain plantings included Amidon spring wheat and spring seeded Neeley winter wheat. Grass species represented those that might typically be recommended under dryland conditions, are adapted to many sites throughout Montana, and provide some protection against non-point source pollution based on growth characteristics of the individual species. Small grains were selected to analyze the

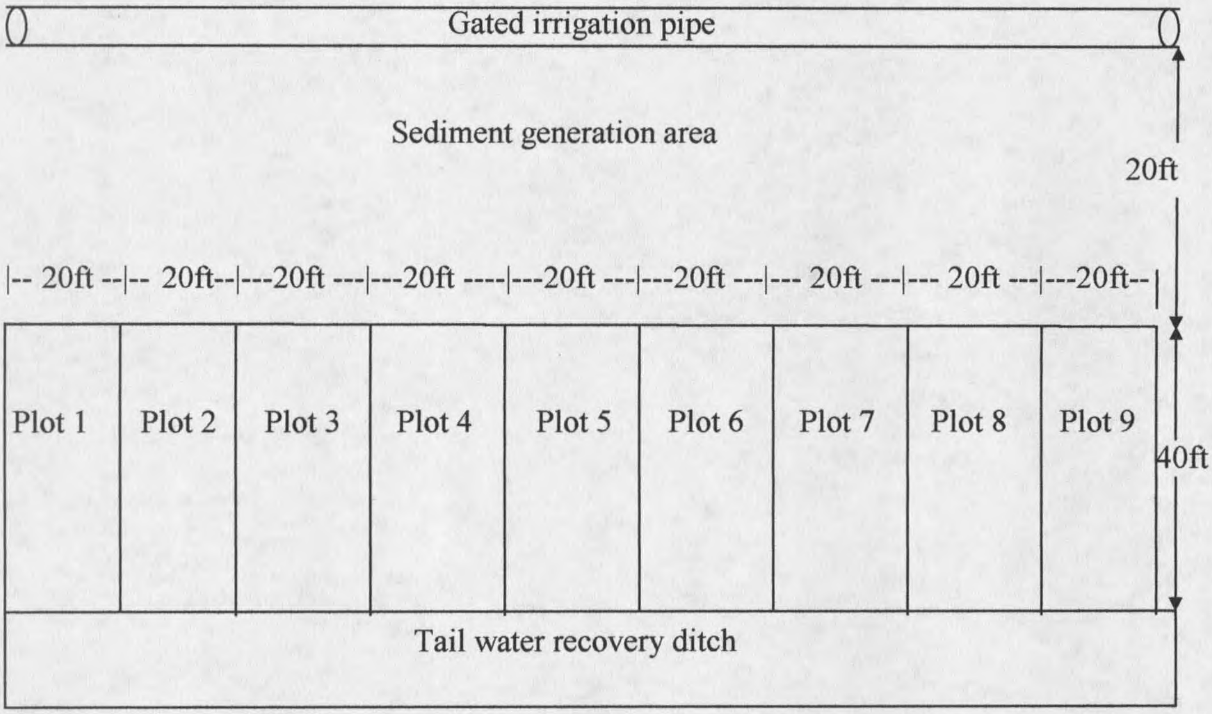

Figure 1. Schematic diagram of a single block of experimental plots.

potential use of annually seeded crops as a vegetative filter strip. The site was prepared by a combination of mechanical and chemical summer fallow in 1995, utilizing a low density small grain cover crop to protect it from erosion. Final seedbed preparations were completed mechanically in spring of 1996, including a final operation of leveling using a land plane to assure uniformity of plot grade and seed to soil contact.

Plot Construction

In spring of 1996, an International Harvester No. 10 grain drill, with seven-inch double disc openers, was calibrated to seed the desired density of each grass and crop species. This grain drill was selected for seeding under the premise that most producers would utilize available on-farm equipment to establish VFS. Design seeding rates were obtained from the Montana Interagency Plant Materials Handbook (April 1990), which is a collaboratively developed reference guide completed by the USDA NRCS and Montana State University Extension Service. Table 2 summarizes the design seeding rate for each vegetative species.

Table 2. Design seeding rates for VFS.

Species and Variety	Drill Setting[a]	Pounds per Acre (PLS)
Manchar smooth bromegrass	20	7.1
Luna pubescent wheatgrass	0	13.4
Hycrest crested wheatgrass	0	21.4
Rosanna western wheatgrass	0	10.4
Rush intermediate wheatgrass	0	10.3
Critana thickspike wheatgrass	5	5.6
Amidon spring wheat	--	1.2 bu/ac
Neeley winter wheat	--	1.0 bu/ac

Note that a setting of zero indicates the drill was set at the lowest possible setting.

Seeding of perennial grasses took place on April 23, 1996. The plots seeded to perennial grasses were allowed to establish for one season prior to data collection. The two grain plots and the fallow plot of each replication, in addition to the source area, were seeded with a low density of barley cover crop to protect them from erosion in 1996. The small grain VFS plots were seeded in spring 1997. All plots were seeded perpendicular to grade. In June of 1997 and 1998 herbicide was applied to all plots to control broadleaf weeds. Glyphosate was applied to weeds in the source area two weeks prior to data collection. Spring wheat plots were sprayed with glyphosate prior to heading each year to keep grain from setting seed. Just prior to each erosion generation period, the sediment source area was tilled to approximate actual cropland soil conditions of an erosion susceptible field. At the same time, fallow control plots were tilled to approximate actual clean-tilled summer fallow conditions. The plot preparation described above attempted to approximate actual cropland soil conditions; however, field conditions and sediment losses from real cropland fields will undoubtedly vary from producer to producer and with different field conditions.

A tailwater recovery ditch was constructed at the bottom of each plot to gather and direct runoff off of the study site. A hand-laid sprinkler irrigation system was then used to saturate the sediment source area and the VFS plots just prior to sediment generation. Filling the soil profile to water holding capacity made it possible to assess effectiveness of individual vegetative species and minimize the effects of variable water infiltration. The experiment was performed twice under saturated profile conditions and once under dry profile conditions.

Biomass measurements were completed for each plot to determine relative above-ground vegetation produced from each species. Measurements were taken by clipping vegetation at ground level at three randomly selected sites within each plot, air dried and weighed. Means of the results were recorded. Biomass measurements were completed in 1997 and 1998 directly after experimental procedures concluded. Data were subsequently analyzed to determine relationships to hydraulic flow reduction and sediment removal.

Basal area measurements were completed for each species to analyze potential relationships to hydraulic flow reduction and sediment removal. Basal area was determined by using a line transect method parallel and perpendicular to established rows within each plot, summing the total inches of basal area in 3-feet length at each one-inch intercept, and calculating the percentage of total basal area. Measurements were recorded just prior to running the experiment in 1997 and 1998.

Runoff Simulation

At the cessation of sprinkler irrigating the VFS and source area, the source area was essentially flooded, using gated pipe, to generate sediment flow onto the VFS treatments. Water was applied to one plot at a time while data were being collected. The same number of gates on the gated irrigation pipe was opened as each plot was treated to ensure that consistent water application was achieved. Water application to the source area was measured at each plot by recording the time it took to collect a predetermined amount of water flowing out of a single gate, then multiplying the result by the number of gates opened. Water application the first and second year equated to 3.32 inches of rainfall in a 24-hour period and 3.30 inches in a 24-hour period, respectfully, during the wet soil profile runs. The third run, where the soil profile was dry, water application equated to 5.8 inches of rainfall in a 24-hour period. The difference in water application rates between the wet and dry soil profile runs is a potential source of variation among the results since soil erodibility and infiltration are spatially variable even within the same contiguous soil unit. However, the dry soil profile run was completed as a comparison to the wet soil profile run, was analyzed separately, and is not considered in the statistical analysis of the effectiveness of the vegetative species. The simulated runoff events on the wet soil profile closely approximated a 50-year recurrence interval, 24 hour duration in Montana. The dry profile simulation closely approximated a 100-year recurrence interval, 24 hour duration event in Montana.

Sampling Procedures and Analytical Techniques

Rate of advance of the wetting front through each VFS was recorded during each runoff simulation. Beginning at the time runoff water entered the upslope edge of the VFS and at subsequent 10-second intervals, a flag was placed at the point of furthest water advancement within each plot. At the instant runoff began to exit the lower end of the VFS, five water quality samples were collected in succession from the end of each plot. Water quality samples were collected from all plots including the clean-tilled fallow "control", the perennial grass species, and the small grain plots with each runoff simulation. Water samples were immediately transferred to 1000 ml Imhoff cones. Sediment was allowed to settle out of solution for 15 minutes, at which time the settled sediment depth within each cone was recorded. To accelerate sediment flocculation within the cones, 20 ml of one-percent concentrate of aluminum sulfate (alum) was placed into each cone prior to the addition of plot water samples. Use of Imhoff cone method was calibrated and followed according to procedures stated by Sojka et al. (1992). Actual sediment concentration was determined from calibration equations.

Imhoff Cone Calibration

Calibrations for the Imhoff cones and the Heldt silt loam soil were used to relate depth of settled sediment in a 1-liter Imhoff cone to actual suspended sediment load in a 1-liter soil water sample. To develop the calibrations, bulk soil samples were collected from the 0-2 inch depth at four locations within the VFS study area. Samples were collected in August 1997 at the time the first VFS experiments were run. Soil samples were air-dried and sieved to retain soil aggregates less than 2-mm diameter. A calibration curve between actual and settled sediment depth was determined using 5, 10, 20, 40, 80, and 160 grams of soil per liter of sample volume. Triplicate samples of these six concentrations were combined with 20 ml of concentrated solution of aluminum sulfate (commercially available alum) to promote flocculation, dispersed by shaking, and allowed to settle 10 and 20 minutes, after which the settled depth of sediment was determined. Table 3 shows the recorded cone readings during the 10 and 20 minute replicates. The settled volume/depth (grams) was plotted against soil added (grams). Data corresponding to the 10-minute and 20-minute readings were plotted on a single graph. A calibration curve was then developed by regressing soil added (grams) versus settled volume/depth (grams) (see Figure 2). Also included is the regression equation, relating Imhoff cone reading to actual sediment concentration.

Table 3. Imhoff cone soil calibration data.

Soil added to 1-liter of water* (grams)	Imhoff Cone Settled Volume Reading 10-minute replicate			20-minute replicate		
	1	2	3	1	2	3
5	6.5	6.0	6.5	7.0	6.25	6.75
10	10.8	11.4	11.6	11.9	12.2	12.1
20	24.0	21.0	22.5	25.0	22.0	23.9
40	44.0	43.0	46.0	46.0	45.0	48.0
80	84.0	84.0	85.0	86.0	87.0	88.0
160	160.0	160.0	160.0	167.0	170.0	170.0

* Tap water was used to represent a quality similar to that of the actual irrigation water.

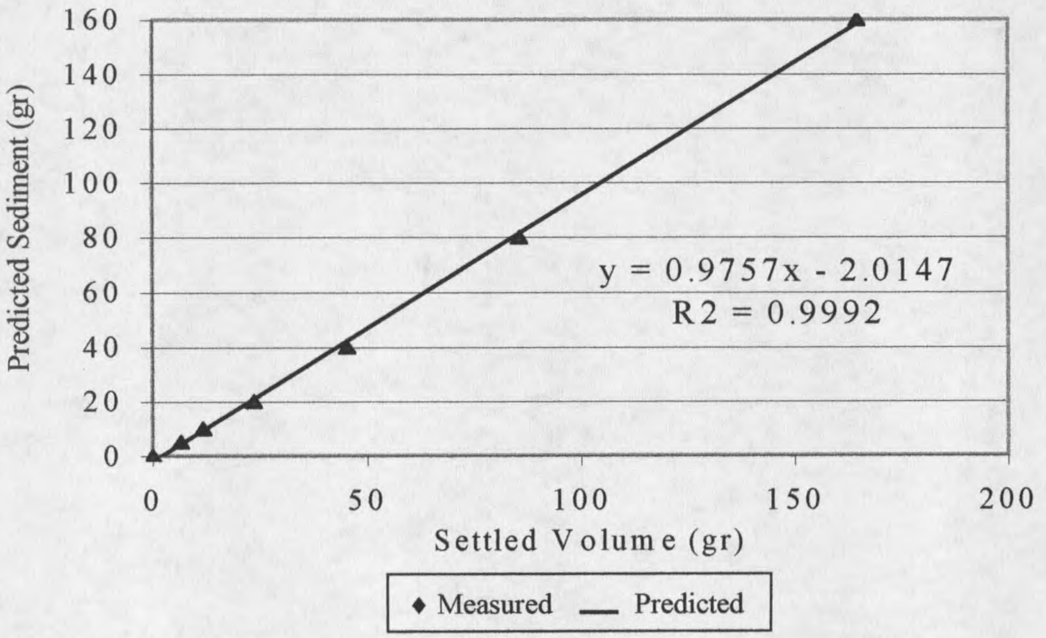

Figure 2. Imhoff cone calibration regression analysis

CHAPTER 3

RESULTS AND DISCUSSION

Overview

In this study, runoff was initiated by flooding a sediment generation area and VFS with water volumes equivalent to 3.3 in (84.3 mm) and 3.3 in (83.8 mm) of rainfall in a 24-hr period on wet soil profiles and 5.8 in (147 mm) of rainfall in a 24-hr period on dry soil profile. It should be recognized that these conditions constitute extreme precipitation events (return period > 50 years on wet soil profiles, >100 years on dry soil profile) and consequently, the simulations produced more runoff and sediment than would be expected under normal conditions. Results presented in this research should be interpreted with these considerations in mind.

Table 4 presents ANOVA results for concentration of sediment in runoff, rate of advancement of the wetting front through plots, vegetative biomass, and basal area. Statistical analysis was completed independently for each experiment.

Runoff simulation techniques performed well during experimental procedures. The mean application rate of water over the sediment source area was 3.3 in (84 mm) per 24-hr period and ranged from a low 2.4 in (61mm) to a high of 4.8 in (122 mm) per 24-hr period.

Sediment Concentration

Analysis of variance and means separation indicated significant differences in sediment concentration of runoff among the various grass or small grain species and significant differences between the vegetated filter strips and the fallow treatments (Table 4). All of the VFS were effective for sediment removal compared to the clean-tilled fallow control for both wet and dry soil profile experiments, as shown in Table 5, Figure 3, and Figure 4. Mean sediment concentrations in runoff from the fallow control plots were 17.7, 15.7, and 69.1 g/L (2.0, 1.8, and 7.8 t/acre-inch), respectively, for experiment 1, 2, and 3. Sediment concentration in runoff from plots with vegetation was significantly reduced ($P < 0.0001$) and ranged from 2.10 g/L (0.2 t/acre-inch) to 16.9 g/L (1.9 t/acre-inch), with the exception of two VFS during the first year of establishment. During the first year after planting, western and pubescent wheatgrass had not established sufficiently to significantly reduce sediment transport through the VFS. Concentration of sediment from these strips was 15.8 and 12.9 g/L, respectively (Table 5). Winter wheat and thickspike wheatgrass reduced sediment transport the most during the establishment year, resulting in sediment concentrations of 2.1 and 4.7 g/L, respectively, in runoff. In the initial year of establishment, VFS that were composed of species with high rates of establishment (reflected in high basal area percentage, Table 5) reduced the concentration of sediment in the runoff from VFS the most. Spring-seeded winter wheat, crested wheatgrass, and thickspike wheatgrass (basal area 15.2, 17.2, and 9.8 percent, respectively) reduced sediment concentration the most in relation to fallow (15.6, 12.6, and 13.0 g/L, respectively).

Table 4. F-statistic from ANOVA for sediment concentration, water advancement through VFS, vegetative biomass, and basal area calculated from pooled and individual analysis of variance for VFS.

Source of variation	df	Sediment Concentration	Water Advance	Biomass	Basal Area
		Experiment 1 (wet soil profile)			
Block	2	0.94^{NS}	2.63^{NS}	3.11^{NS}	5.33*
Treatments	8	1.76^{NS}	1.38^{NS}	9.18***	108.99***
Fallow x species	1	65.96***	3.90^{NS}		
r^2		0.795	0.505	0.833	0.982
CV, %		45.9	25.0	32.9	10.5
		Experiment 2 (wet soil profile)			
Block	2	3.27^{NS}	2.45^{NS}	1.43^{NS}	4.41^{NS}
Treatments	8	5.25**	6.02***	13.23***	71.20***
Fallow x species	1	38.02***	10.29**		
r^2		0.752	0.768	0.872	0.973
CV, %		46.5	36.7	34.4	14.3
		Experiment 3 (dry soil profile)			
Block	2	0.94^{NS}	2.26^{NS}		
Treatments	8	17.30***	1.30^{NS}	(not measured)	
Fallow x species	1	1034.95***	7.34^{NS}		
r^2		0.926	0.482		
CV, %		29.7	44.0		

*, **, *** Significant at the $P = 0.05, 0.01, 0.001$ levels, respectively.
^{NS} Not significant.