Assessing Reduction of Soil Erosion in Row-Crop-Prairie Systems Through Mixed Effect and Simulation Modeling

by

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Abstract

Reducing soil erosion is imperative to maintain global food production, clean water, and habitat. It is also a leading conservation priority in the U.S. Corn Belt, where soil loss represents a financial liability for farmers and an ecological health risk downstream. A conservation technology involving strips of reconstructed native prairie vegetation is receiving attention as a strategy to minimize erosion. Along contours or in high-risk areas, strips of the perennial prairie vegetation are strategically installed in annual corn and soybean row-crop fields to slow and reduce the movement of water and capture sediment, among other functions. In this analysis, I collaborated with the Science-Based Trials of Rowcrops Integrated with Prairie Strips (STRIPS) project at Iowa State University to examine and model soil movement in crop fields that include prairie strips.

This research is composed of two complementary parts. First, I compared in-field erosion between treatment sites incorporating prairie strips and control sites entirely consisting of annual row-crop cover. Data were analyzed using a mixed effect statistical model, which showed that prairie strip treatment reduced erosion by 33% compared to the control. Second, I investigated the potential of the USDA Water Erosion Prediction Project (WEPP) model to more broadly predict soil and water dynamics within integrated row-crop-prairie systems, in which 10–20% of annual crop field land cover is replaced by prairie vegetation strips. My predictions for sediment export, in-field displacement, and runoff within WEPP corroborate empirical evidence of soil and water conservation through prairie strip technology. According to multi-year simulations of twelve no-till fields in Iowa, prairie strips decrease sediment export by an estimated 97%, runoff by 27%, and soil displacement by 55%. Empirical measurements of sediment export and runoff were available for the same watersheds, similarly showing a 96% reduction in sediment export on prairie strips and suggesting up to a 45% reduction in runoff.

In summary, this research shows that prairie strip conservation technology significantly reduces erosion and sedimentation, and that WEPP is an effective tool to predict the benefits of this technology. Multi-year WEPP simulations, with the calibrations developed in this paper, may help farmers visualize and predict the long-term effects of prairie strip integration, helping inform land management decisions. This research can further the development of solutions to the widespread challenge of soil erosion, helping conserve current and future food production in the U.S. Corn Belt and beyond.

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Introduction

On a planet with increasing pressures on limited resources, effective and efficient solutions for natural resource conservation are critical to ensure societal and ecological wellbeing (Perrings, 2014; Djoghlaf and Dodds, 2011). Humans have increasingly profound and rapid influence on the quantity and quality of natural resources through decisions about how land is used, and the impacts of land use change extend not simply locally but also globally (Zhan, 2015; Thornton, 2010). Shrinking and fragmented areas of habitat that drive biodiversity loss in terms of both local and global species extinctions in turn put pressure on ecosystem function (Djoghlaf and Dodds, 2011) and can increase the susceptibility of ecosystems and humans to diseases (Dirzo et al., 2014; Young et al., 2014). Land use change can also exacerbate effects of climate change and rates of pollution and soil degradation (Fall et al., 2010; Delkash et al., 2018; Bosetti and Lubowski, 2010; FAO and ITPS, 2015).

Large-scale agriculture is at the intersection of these issues, managing large expanses of land and the resulting ecological impacts, while simultaneously working through how to provide the energy, materials, food, and space demanded by an increasing population. Farmers also face pressure to be economically judicious in decisions about inputs and management to ensure sustained profitability amidst uncertainty of climatic conditions and market behavior (Prokopy et al., 2015; Dismukes et al., 1997).

Agricultural decisions that modify landscapes and function by extension also impact the resilience of the ecological system and the cycling of nutrients and resources (see for instance, Matsushita et al., 2016; Schaller et al., 2018; Evans and Potts, 2015; D'Acunto et al., 2018; Burke et al., 2016). The current industrial approach to agriculture has succeeded in increasing the predictability and performance of several remarkable crops, providing food, fiber, animal feed, and fuel for 7 billion-and-growing global citizens. The industry has adopted inputs such as synthetic fertilizer and sown acres of genetically similar or identical crops to increase the consistency and ease of harvest. However, this current approach also has key problems that must be addressed if continued success is to be expected. The fertilizer required to replace nutrient losses on annual row-crop fields generates a waste stream leading to toxic buildup of phosphorus and nitrogen in rivers and ocean bays (Jones et al., 2018; He and Xu, 2015). Meanwhile, vast monocultures provide little genetic diversity or natural habitat.

Critically, agriculture plays a large role in soil degradation. A total of 75 billion metric tons of soil erode annually, with two thirds of this occurring in agricultural areas (Myers, 1994). Erosion affects 1.6 billion hectares worldwide and is responsible for 84% of cropland degradation (Oldeman et al., 1991). Land productivity losses due to erosion contribute to inadequate nutrition among low-income countries and are becoming increasingly important as projections for annual yield growth decline (Wiebe, 2003).

Adopting a land use framework based on ecosystem services, defined as the benefits that people receive from the environment, can illuminate a path forward that provides for humans and ecosystems both on-site and downstream (Daily and Matson, 2008). Increasing constraints on resources necessitate land-use decisions that not only supply “food, feed, fiber, and fuel,” but also replenish and retain soil, protect pollinators, preserve genetic resources, resist disease, and provide inspiration and enjoyment (Millennium Ecosystem Assessment, 2005; Díaz et al., 2018). Effective large-scale agriculture requires intentionality in maximizing the uses of the land and expanding our understanding of the benefits provided by human-environment systems.

Erosion and Runoff in Iowa

In Iowa, the heart of the U.S. Corn Belt, farm fields typically lose over 11 Mg/ha (5 short tons per acre or t/ac) of soil per year, totaling a loss of 6.8 inches of topsoil since 1850.[1] However, the "average" soil loss is not an accurate picture of what truly occurs on the field throughout the year. The most intense erosion comes from extreme weather events that occur over the course of a day or even hours. For example, during a downpour in May of 2007, 182 Iowa townships encompassing 4.2 million acres lost over an estimated 5 tons of soil per acre (11 Mg/ha) in a single day. Of these, 14 townships are estimated to have lost over four times this amount. Between 2002 and 2010, annual average erosion in 257 townships exceeded an estimated 50 short tons per acre (110 Mg/ha) (Cox et al., 2011).

For farmers, this matters because soil is a highly valuable resource. Land is priced according to its suitability for row-crop cultivation—areas with the highest Corn Suitability Rating can rake in well over $12,000 per acre. Erosion also leads to loss of soil minerals and nutrients needed for optimal crop productivity (DeLong et al., 2015), and poor soil quality can exacerbate flooding that leads to crop damage. Furthermore, valuable inputs such as pesticides and fertilizer wash downstream alongside sediment, representing a significant economic cost for farmers.

[1] At a conservative estimate of 5.5 tons/acre, based on the 25-year average annual sheet- and rill-erosion in Iowa, from the NRCS National Resources Inventory (USDA NRCS, 2009).

Offsite, erosion and sedimentation cause additional problems. The inputs that improve productivity on the field are a health hazard in the drinking supply and threaten aquatic ecosystems downstream. On a broader scale, sedimentation resulting from Corn Belt agriculture has long disrupted aquatic ecosystems (Blann et al., 2009; Riseng et al., 2011). Sedimentation in agricultural streams reduces algae and invertebrate biodiversity, especially when combined with an increase in stream temperature (Piggott et al., 2012). Fine sediment particles also compromise trout and salmon habitat, diminishing growth and survival (Tappel and Bjornn, 1983; Sigler et al 1984). In marine ecosystems, dirt particles and chemicals present in agricultural runoff are contaminants rather than assets, and the excess nitrogen and phosphorus allow for an explosion of nutrient-hungry algae that create the so-called "dead zones" in coastal waters. In the summer of 2017, the resulting "dead zone" at the mouth of the Mississippi exceeded 8,776 square miles, in which thick blooms of algae snuffed out fish and plant species by consuming all available oxygen and light (NOAA, 2017). The movement of agricultural nutrients off-site, then, causes two imbalances: first, losing value where it is needed and second, depositing pollutants to sensitive ecosystems downstream.

Erosion Processes and Modeling

Erosion is the surface movement of soil from one place to another elicited by an agent such as wind, water, or glacier. On agricultural landscapes, rainfall and tillage dislodge aggregates, leading to water erosion and tillage erosion that impacts the quality, quantity, distribution, and future erodibility of the soil (Osman, 2013; Van Oost et al., 2003). There are four types of water erosion. Sheet or inter-rill erosion occurs when precipitation splashes and displaces soil particles, and the water runs down a plane rather than concentrating in rivulets. Rill erosion, gully erosion, and streambank erosion occur when water carves out channels in the soil to form small rills, large gullies, or entire streambeds, respectively. Many gullies on crop fields are ephemeral, or seasonal, and disappear when the soil is disturbed for harvest or tilling (Foster, 1986).

Some sediment—tiny soil fragments transported by water—reaches the bottom of the watershed and can be recorded with an H-flume or other monitoring technology. In this paper, I use the term “sediment delivery” or “sediment yield” to refer to the rate at which sediment leaves the watershed, in terms of mass per unit of area. The water that leaves the watershed and is not absorbed into the ground is “runoff.” However, not all erosion involves soil particles carried to the bottom of the watershed and beyond. Rather, some sediment is deposited within the field, further downstream. The WEPP graphical user interface uses the term “Soil Loss,” but to avoid confusion with the particulate lost from the watershed, I use “In-Field Soil Displacement” in this paper, or simply “Displacement.” In-field soil displacement refers to the rate at which soil is being dislodged from the hillslope, in terms of mass per unit of area.

There are many methods for quantifying erosion and sedimentation, including volumetric and dynamic empirical field data collection techniques such as erosion pins (metal rods driven into soil that become increasingly exposed with erosion) and H-flumes, respectively, as well as models such as WaTEM, RUSLE, and WEPP. This paper focuses on two methods: an empirical dynamic field data collection technique known as the mesh pad method, which can spatially estimate displacement, and the WEPP simulation model, which can estimate displacement, runoff, and sediment delivery.

WEPP as a Modeling Tool

The Water Erosion Prediction Project, or WEPP, is an erosion and runoff prediction tool developed by a team of scientists from the U.S. Department of Agriculture. It was commissioned for use by the Soil Conservation Service, Forest Service, and Bureau of Land Management in 1985, and it was released in its initial version in 1995 (Flanagan and Livingston, 1995). In 2017, the Natural Resources Conservation Service of Iowa began transitioning from its existing model, the Revised Universal Soil Loss Equation (RUSLE) with the more fine-tuned, customizable WEPP to assess the impacts of land management practices on soil erosion (USDA NRCS, 2017).

WEPP and RUSLE differ in several important aspects. The first is that RUSLE is only able to predict soil export from a field, while WEPP also predicts soil displacement from one area of the field to another. This difference allows the predictions of WEPP to be tested using an in-field erosion measurement known as the mesh pad method, which can estimate soil displacement within the field, whereas RUSLE may only be tested through sediment collection at the bottom of the watershed. Sediment collection requires manipulation of the watershed, which is more invasive than the mesh pad method and therefore less representative of the true landscape (Hsieh et al., 2009). In addition, RUSLE is a much coarser prediction and uses only a few set multipliers, while WEPP includes dozens of parameters that can be adjusted for optimal prediction of hydrologic behavior. It simulates hundreds of hydrological processes, including sediment transport and deposition, surface runoff, flow shear stress, and soil water percolation, and it incorporates information on factors such as irrigation, tillage, land cover, and crop productivity (Flanagan, 2013). It can utilize real climate records or stochastically generate its own based on 30 years of data (USDA NRCS, 2017). WEPP has two modes for application: on the small scale for individual hillslopes, or on the large scale for entire watersheds.

These advantages have contributed to the success of the WEPP model in a variety of scenarios, including forest management, irrigated agricultural systems, construction sites, and mountain ranges (Elliot and Hall, 1997; Bjorneberg et al., 1999; Pudasaini and Riley, 2004; Pieri et al., 2007). Most relevant to this paper is the use of WEPP to predict soil erosion and surface runoff in agricultural Iowa townships (Cruse et al., 2006).

In this study, I investigate the potential of WEPP to predict erosion and runoff data from the STRIPS Conservation Project on agricultural landscapes that integrate native perennial vegetation with annual corn and soybean fields. To do this, I compare WEPP model results to a set of erosion and runoff data from conventional and conservation row-crop systems in Iowa that have incorporated strategic plantings of native perennial vegetation.

STRIPS Conservation Project

Science-Based Trials of Rowcrops Integrated with Prairie Strips, or STRIPS, is a multidisciplinary project investigating the potential to achieve multiple on-site and downstream ecosystem services by integrating small areas of diverse, native perennial prairie into annual corn and soybean row-crop fields (“STRIPS”, available at https://www.nrem.iastate.edu/research/STRIPS/). The strategy is a multifunctional step to achieving Iowa’s nutrient reduction goals, reducing losses for farmers, increasing habitat for at-risk species, and increasing the quality and functionality of Midwestern cropland

(Schulte et al., 2017). It involves a team from Iowa State University and collaborating farms/organizations in a variety of disciplines including hydrology, ecology, soil sciences, entomology, statistics, social science, and environmental economics. The project currently exists on 54 sites throughout Iowa and neighboring states, representing over 559 acres of planted prairie vegetation protecting 4609 acres of farmland (Lisa Schulte Moore, Iowa State University, personal communication, 2018).

The prairie vegetation planted in the strips has a very different structure from that of the annual row-crops, both above and below ground. Corn and soybeans are planted in rows, usually 30 inches (76 cm) apart for corn (Corn Row Spacing, 2018), and 15 or 30 inches (38 or 76 cm) apart for soybeans (Iowa State University Extension and Outreach, 2018). Between these rows is bare ground and/or crop residue from the previous harvest. Occasionally, a handful of annual weed species grow among the crops. By contrast, plant spacing in reconstructed prairie areas is tight, and includes a rich diversity of forbs, cool-season grasses, and warm-season grasses, providing a more consistent cover throughout the non-freezing season. Little bare ground is usually visible, and the soil is often covered with a layer of litter.

Typically, farmers interested in soil conservation plant a low-diversity mixture of cool-season exotic grasses, such as brome, in a buffer or grassed waterway. These plants have thin stems that bend easily in wind or in high-runoff events, creating a slippery mat over which water flows quickly, reducing absorption into the soil. By contrast, the thick, tightly-spaced stems and litter cover in prairie ecosystems slow down the flow of water and the movement of suspended soil particles, providing a mechanism for capturing sediment and reducing runoff.

Furthermore, although the annual corn plants, soybean bushes, and weeds in row-crop fields, as well as the exotic annual grasses in many traditional grassed waterways, produce a great deal of above-ground biomass, they do so at the expense of investing in deep, stable root systems such as those created by perennial plants. Perennial prairie species, conversely, build deep, fibrous root structures. These root systems hold onto aggregates and contribute organic matter to the soil, providing another mechanism for erosion control.

Pollinators also benefit from the high diversity of prairie flowering species. While soybeans all flower at the same time and are often sprayed with pesticides that can damage pollinator populations, the species in tallgrass prairies include a range of blooming habits, allowing pollinators to use them for a greater portion of the year (Anderson and Schelfhout, 1980).

The first phase of the STRIPS project consisted of a study of 12 small agricultural watersheds at Neal Smith National Wildlife Refuge (NSNWR). Sites included either 0%, 10%, or 20% prairie land cover arranged in contour strips or aggregated at the lowest elevation, or footslope, of each watershed (Hernandez-Santana, 2013). The team hypothesized that prairie strips would produce ecosystem services at levels disproportionate to their physical extent within the catchment. Research from Phase One demonstrated that incorporation of prairie strips into row-crop areas is an effective conservation strategy in obtaining critical soil, water, and biodiversity ecosystem services for Corn Belt agricultural areas. Prairie strip installation in 10% of the cropland led to less watershed export of dissolved organic carbon (Smith, 2014) and increased denitrification enzyme activity important for potential long-term nitrate removal (Mitchell et al., 2015).

Diversity and continuous abundance of perennial flowering plants was positively correlated with diversity and abundance of beneficial insects (Gill et al., 2014), and small amounts of prairie led to substantial increases in bird abundance, number of species, and diversity (Schulte et al., 2016). Most importantly for this project, prairie integration reduced the export of soil by 96%, phosphorus by 90%, and nitrogen by 84%, and decreased surface runoff by 37% (Helmers et al., 2012; Zhou et al., 2014; Hernandez-Santana et al., 2013).

The project is now in Phase Two, which extends the multidisciplinary watershed-based work of Phase One to commercial farm fields across Iowa and surrounding states. In Phase Two, farmers and researchers collaborate to build and monitor large-scale, integrated prairie-row-crop systems in for-profit farms extending up to thousands of acres. The prairie species composition and configuration of each site is custom-designed to accommodate watershed topography, farm equipment accessibility, and local climate. A variety of labs within the STRIPS team monitor the sites for water quality, soil quality, yield, and various dimensions of biodiversity including birds, snakes, rodents, bees, and beetles. Prairie strip "treatment" data are contextualized by "control" data taken from six paired sites with similar topographic and climate characteristics that do not integrate prairie vegetation.

Context of This Research

In Phase One of the STRIPS Project, extensive data were collected on watershed runoff and sediment delivery, but the movement of soil on the field was less understood. Following installation of hydrological monitoring instruments in 2015, three years of in-field soil displacement data have been collected in Phase Two. Analysis of the new displacement data conducted in this study is intended to shed light on in-field soil processes and the extent to which prairie plantings can curb movement in row-crop portions of the field.

Although in the STRIPS Project the performance of prairie strips is carefully monitored after the fact, no simulation or prediction capability currently exists for soil and water metrics on a particular potential site. The motivation behind the simulation modeling in this study is that WEPP has the potential to predict outcomes for a broad variety of topographies and soil types, as well as provide farmers with predictions of potential savings in terms of soil and water.

Performance of prairie strips in the first few years is especially unpredictable. As the land recovers from disturbance it passes through weedy stages that can be distressing and "ugly" to farmers. The flexibility of WEPP to accommodate a variety of vegetation and biomass efficiency scenarios could help generate reasonable and accurate first-year simulations of vegetation, erosion benefits, and biomass.

Currently, prairie strip installation poses several practical challenges for farmers that could be alleviated through the use of WEPP modeling. Prairie strip consultation is currently conducted by hand and undergoes several iterations to optimize for topography, hydrology, crop yield requirements, and equipment constraints. This design process is conducted without the aid of modeling software that could simulate the effects of various decisions. The WEPP software could be easily and efficiently combined with freely-available LiDAR data and a partner institution's ArcGIS platform, enabling farmers to set geographical and physical constraints on their model tailored to their specific watershed and receive real-time estimates. In the future, this potential may expand to yield predictions and input requirements to inform farmer decisions and predictions for the first few years, such as determining how much prairie is economical to install for a particular site. This capability could boost the confidence of farmers and increase likelihood of adoption of this promising conservation technology.

Objectives

Reducing soil erosion is a leading conservation priority for farmers in Iowa. In a 2012 survey, 75% of Iowans reported that they were "concerned" or "very concerned" about soil erosion (Arbuckle et al., 2015). With this priority in mind, this paper aims to understand soil movement in row-crop fields and investigate the potential of prairie strip technology to reduce the loss and displacement of soil in agricultural landscapes. As a step toward predicting the likely impact of prairie strips, this study incorporates WEPP modeling.

I sought to tackle two overarching questions in this study. First, what is the impact of prairie installations on sedimentation, runoff, and in-field soil displacement in annual crop fields? Second, how do model-based estimates of field-level sedimentation, runoff, and displacement in a row-crop-prairie conservation agriculture system compare to empirical estimates? My objective with the first part of this research was to ascertain whether prairie strips decrease in-field soil displacement, through analysis of soil movement data collected from mesh pads. I sought to answer the question: Do prairie strips decrease in-field soil displacement? I had two primary objectives in conducting the WEPP modeling component. The first was to determine: Is the potential of prairie strips to decrease sediment yield supported by the WEPP model? The second objective was to ascertain: Can WEPP help farmers predict the changes in soil and water movement (specifically, sedimentation, runoff, and in-field displacement) that they would see on their fields after installing prairie strips?

Methods

Part One: Empirical In-Field Displacement Analysis

In Part One of this study, we investigate the impact of prairie strip installation on in-field soil displacement by analyzing empirical data gathered by the STRIPS soil lab in a matched pairs experiment including STRIPS sites throughout Iowa. The team deployed sets of mesh soil pads on small agricultural watersheds in Iowa, USA between 2015 and 2017, recording in-field soil erosion during the rainy season in annual corn and soybean crop fields. The design and deployment of mesh pads was based on the mesh pad methodology developed by Y.P. Hsieh (Hsieh, 1992; Hsieh et al., 2009). The mesh pads measured 15 cm x 15 cm and were made of two layers: a bottom layer of extra-fine no-see-um netting (Barre Army Navy Store, IN-009) and a top layer of coarse polyester mesh (Jason Mills, Style 78). The pads were arranged in three rows of ten, at the shoulder (upper elevation), backslope (middle), and footslope (lowest elevation) of each slope. For watersheds containing prairie strips, a strip was located between the row of mesh pads at the shoulder and the row at the backslope. Lateral spacing of the mesh pads along each row measured 10 m. Each of the seven sites monitored, with the exception of the NSNWR site, included one watershed with a paired set of fields: a control field of 100% row-crop and a treatment field including installations of native prairie vegetation strips. The NSNWR site contained six studied watersheds, each including a control/treatment field pairing. Survey periods were divided into three categories (early, mid, and late season) based on the deployment and retrieval date of the mesh pads.

In this paper, a mixed effect model, lmer1, is used to compare erosion between treatment sites incorporating perennial prairie vegetation strips and control sites consisting of 100% annual row-crop cover. The mixed effect model was constructed to estimate the effect of treatment on row-crop hillslopes, adjusting for year, survey, crop, and position as fixed effects. Site was modeled as a random effect, to represent the choice of the particular studied sites from many possible sites. Finally, a type III Sum of Squares was conducted to obtain F Values for the fixed effects. Analysis was conducted in R version 3.4.1 (Urbanek and Bibiko., 2017; available at https://www.r-project.org/), using the lmer function (v1.17) in the lme4 package for model construction (Bates et al., 2017; available at http://lme4.r-forge.r-project.org/) and the Anova function in the car package (v2.5) for the analysis of variance (Fox and Weisberg, 2017; available at https://CRAN.R-project.org/package=car). The lsmeans and contrast functions in the lsmeans package (v2.27-2) were used to estimate the multiplicative effect of prairie strip treatment, and the confint function from the lsmeans package was used to estimate the confidence interval (Lenth, 2017; available at https://cran.r-project.org/package=lsmeans).

Erosion estimates are expressed in terms of soil g (dry weight) per day per pad, then extrapolated to a daily raw mean of tonnes per hectare (Mg/ha) per day. For this conversion, values were multiplied by 4/9 to convert from g per 15*15 cm pad to tonnes/hectare. The soil pads were only deployed during the rainy season so an annual erosion estimate is not made. Because the data are heavily right-skewed, the data were log-transformed before being fit with a mixed effect model. This leads to a calculated treatment effect that is less pronounced than the ratio of the raw means alone, and it enables the coefficient of treatment to be interpreted as a multiplicative effect.

Part Two: WEPP Simulation Analysis

The second part of this study uses simulations in WEPP to investigate the impact of prairie strip installation on off-site sediment export, runoff, and in-field soil displacement. STRIPS1 watersheds located on the NSNWR site are modeled using WEPP, and results are compared with empirical data from each watershed.

For this analysis, the WEPP hillslope model, which models rill and inter-rill erosion, was chosen over the watershed model as a simple, efficient option for erosion estimation on small STRIPS sites. Each hillslope in WEPP is treated as a flat region. Although this technique simplifies the hydrology of water flow on a curved surface, it allows for more computationally efficient modeling of large areas. Set-up and parameterization is more streamlined in the hillslope model than in the watershed model, which makes the hillslope model an ideal choice for prairie strip managers or consultants.

To process geospatial data for each site, ArcGIS 10.5 was used to link watershed location with soil, slope, and land cover and size. Watershed shapefiles from the STRIPS lab were used for location of sites and placement of prairie strips, projected using UTM NAD 1983. This information was used to create site-specific soil and slope input files for the simulations.

In addition to soil and slope, WEPP simulations on the NSNWR site also incorporate site-specific data for climate and biomass. Consultation with Dr. Brian Gelder from the Daily Erosion Project identified accurate, high-resolution data for these four parameters as the most critical requirements for strong model performance. This study does not include an analysis of crop yield estimates, since it does not use WEPP to predict crop performance.

The WEPP interface provides a capability to modify and create input files that represent management, land cover and dimensions, soil, and slope. Through the WEPP interface, a user can link these input files to a hillslope model as well as choose from a number of output options.

Initial Runs to Ascertain Effect of Prairie on Sediment Yield

Simulations in WEPP were conducted to determine if the model provides evidence for the potential of prairie strips to decrease sedimentation on crop fields. Soil type, plant cover, and management files were used with default WEPP settings. The generation procedure used for each input is described below.

Climate

For future predictions, WEPP uses a stochastic climate model (CLIGEN) to generate continuous precipitation and temperature data. Because runoff is based on real rainfall events, it was considered especially important for specific years or short time periods to use the most accurate data possible for precipitation, which involved replacing CLIGEN-generated data with real values. Precipitation and temperature data for the watersheds were generated by the Daily Erosion Project, whose model combines and processes NOAA MRMS Radar and Iowa Environmental Mesonet data (Gelder et al., 2017).

WEPP climate data are entered in a text-based file format known as a .CLI file. The .CLI files used in this study were contributed by Daily Erosion Project researchers, who use WEPP for estimating erosion on watersheds throughout Iowa for nutrient reduction goals.

Management

Management information for crop areas was modified from the “corn-soybean-notill” file in WEPP. To match the rotation schedule on the sites, the modified file began with soybeans, rather than corn, in Julian Year One. Timing details such as tilling date, fertilizing date, pesticide application date, and harvest date were not always available for the sites being researched. For this reason, WEPP’s default management practices were used for each land use type.

Mowing of the prairie vegetation occurred three times in the nine-year period and prior studies have failed to identify it as a driving factor of displacement (Moore et al., 2007). For this reason, mowing was not included as a factor in this study.

Land cover

Data about the land cover, length, and width of the hillslope were developed in ArcGIS 10.5 (ESRI, https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview). A mid-range value was selected to estimate length and width of the hillslope as well as the placement and width of prairie strips.

Soil

Soil data comes from the SSURGO database developed by USDA NRCS and is publicly available for download (USDA NRCS, 2014; available at https://catalog.data.gov/dataset/soil-survey-geographic-ssurgo-database-for-various-soil-survey-areas-in-the-united-states-). Soil type for each watershed was determined through ArcGIS analysis.

Slope

The resolution of slope data can have a large influence on WEPP estimates (Moore et al. 2007). High-resolution elevation shapefiles available for major Iowa watershed basins were converted into one-dimensional slope profiles for each site by delineating a representative flowpath. This study utilized the Interpolate Line tool in the 3D-Analyst toolbar to create a path and determine the elevation along this line. Each slope profile was saved as a Microsoft® Excel™ readable file (Microsoft®, 2018, https://products.office.com/es/excel). The SLOPE function was used to calculate the percent slope of each section to generate a series of points approximately five meters apart. These results were translated into WEPP-usable .SLP files through the WEPP

Slope Profile Editor interface. The “Curve” option under “Advanced Settings” was used to smooth the line.[2] The choice of 5 m as the target segment length was the result of consultation with Dr. Brian Gelder to minimize anomalies that arose from over-parameterization in initial runs. A more detailed discussion can be found in Appendix A.

Land Cover Type

There are several kinds of “Bluestem Prairie” built into WEPP, of varying qualities from “poor” to “good” and taken from one of two sites, Kansas or Nebraska. These pre-set plant files all have very similar parameters and produce a relatively similar sediment output. After conducting a rough series of runs just on the I1 slope alone (see Appendix B), “good” quality prairie from Kansas was chosen as the standard. Although Nebraska is both geographically closer to Iowa, the “good” quality prairie from Kansas better reflected the careful management of STRIPS prairie sites and led to a more accurate erosion estimate than did the “fair” quality prairie from Nebraska. WEPP consistently overestimated erosion for all cases, but this option was chosen to approximate the health of well-managed prairie strips and for its prediction of low erosion and low displacement.

Sediment Export

For basic runs, the basic output was used to give an estimate for overall sediment export for the growing season and for comparison with empirical results. For each

[2] WEPP slope files contain a maximum of 50 points with paired x-coordinate and percent slope information.

watershed, a WEPP simulation was run with the basic parameters described above and the calibrated BEINP value for eight years of study from 2007-2014. Each of these results was compared with corresponding empirical sediment export data from NSNWR. This set of empirical data was obtained from the STRIPS water lab, which set up an H-flume on each site as described in Helmers et al. (2012) and recorded sediment export throughout the growing, or non-freezing, season. The length and dates of the non-freezing season, dependent on the frost dates and temperature conditions for each year, are indicated in Table 1.

An aggregate of empirical sediment export was used for each watershed by year and compared pair-wise for similarity to WEPP simulation outputs. Although WEPP integrates outputs throughout the entire year, rather than simply the non-freezing season, the analysis assumed the model and empirical outputs to be comparable. During the winter, WEPP tracks snowfall and ice buildup, factoring them into runoff calculations when temperatures rise above freezing. As the timeframe of empirical data collection included spring melt, I assumed that a reasonable comparison for annual soil and water loss could be made between the two methods.

Table 1: Non-Freezing Season at NSNWR by Year

Year	Start Date	End Date	Length
2007	April 26	October 15	173 days
2008	April 2	November 7	220 days
2009	April 14	November 7	208 days
2010	April 8	November 16	223 days
2011	April 7	October 11	188 days
2012	March 19	September 22	188 days
2013	April 2	October 21	203 days
2014	April 1	November 11	225 days
2015	April 7	November 4	212 days

Plant Parameter Calibration to Improve Predictions

Plant data are one of the four main inputs previously identified as being of critical importance for meaningful simulation results, and therefore a key focus in the model set-up for this paper. While site-specific data could be used directly for climate, soil, and slope, plant parameters required calibration.

Following the initial runs, a calibration of several plant parameters was conducted. A side-by-side comparison of the default settings to simulations with individual parameter adjustments is included in Appendix D. Using alterations recommended in published literature and adjustments designed to better reflect the prairie composition on the strips, calibrated simulations were conducted.

Adjustments were considered for four default parameters at the guidance of Dr. Brian Gelder to improve behavior predictions for the strips. First, the base daily air temperature was decreased from 10°F to reflect the proportion of cool-season vegetation in the prairie seedling mix. A value of 4.4°F was chosen as an estimate of the temperature at which cool-season grasses begin growth (Oregon State Extension).

For the second and third parameters, simulations on the I1 slope on a subset of years (from 2007-2010) were used for calibration. Heavy adjustments to plant spacing had negligible effect on erosion (Appendix D), and no empirical data were available with which to fine-tune the default parameter value. For the main analysis, plant spacing of 0.5 cm was used, slightly less than the default of 0.6 cm.

Based on these calibration runs, the Darcy–Weisbach maximum friction factor was adjusted from the default value of 12 to 136 for the main analysis. Of the parameters adjusted in the calibration phase, the model appeared most sensitive by far to this parameter. Although the default value was 12, the model overpredicted erosion by a factor of 15, and still overpredicted erosion even with a friction factor over 100. In their study “Hydraulic Roughness Coefficients for Native Rangelands” (1992), Weltz et al. recommend a friction factor of 136.53 for tallgrass prairie. Although WEPP input files did not support this degree of accuracy, the floor of 136 was used with much greater success in calibration runs, with in a predicted average sediment delivery approximately 156% of the actual average. Further information on calibration is in Appendix D.

Conversion of available energy and materials into biomass influences hydrologic behavior on vegetated hillslopes. The “biomass energy ratio" (BEINP) is a measure of the efficiency of plants in converting solar energy from photosynthesis to plant material, and it influences predictions for yield and amount of residue after harvest. Biomass data from the row-crop portion of the fields were not always available, so BEINP was not adjusted for corn and soybean land covers. For prairie land cover, BEINP was adjusted to bring mean peak biomass estimates closer to empirical STRIPS site biomass collection data (Landowner Report). The default BEINP of 25 kg/MJ led to a large overprediction in biomass at approximately 18,500 kg/ha, compared to the 9000-14,000 kg/ha found on STRIPS sites. Estimates for biomass production were available through the full output report on each WEPP run. For each year of the simulation, the peak biomass was recorded, after which a mean peak biomass was calculated over all years. BEINP was adjusted until the mean peak biomass came as close as possible to the target value.

Calibrated WEPP Runs

Simulations were run on all twelve watersheds following plant parameter calibration. Three outputs were analyzed in comparison to empirical data: in-field soil displacement, sediment export, and runoff. An 8-year simulation period of 2007-2014 was used, since 2014 was the last year for which complete empirical data were available for both runoff and sediment export.

Multiplicative Effect in WEPP

The multiplicative effect of prairie strips on sediment export and runoff was estimated by comparing WEPP estimated annual averages for sites containing prairie strips to those for sites without prairie strips. This comparison was conducted with the lsmeans package, version 2.27-2 (Lenth, 2017; available at https://cran.r-project.org/package=lsmeans), in R version 3.4.1 (Urbanek and Bibiko., 2017; available at https://www.r-project.org/). This effect was compared with the empirical multiplicative effect, which was similarly obtained by comparing average sediment export and runoff per non-freezing season for sites containing prairie strips to those without.

Sensitivity Analyses

Many of the input files incorporated publicly available, empirical data and WEPP default parameters calibrated by researchers over many years. Three inputs, however—slope, prairie plant choice, and biomass energy ratio—required discretionary interpretation of site-specific information. A sensitivity analysis was conducted to determine the impact of these variables on sediment export. Since the choice of slope was intended to be representative and was not based on any particular watershed, all sites were included in the sensitivity analysis for slope. Similarly, although the I1 site was used to calibrate the biomass energy ratio (BEINP), this value was calibrated based on yield rather than on sediment export. Because the calibration was not tailored to match sediment predictions for I1, the site was included in the sensitivity analysis dataset. On the other hand, since sediment export predictions for I1 were used to calibrate the choice of prairie cover file during initial runs, site I1 was excluded from the sensitivity analysis of prairie cover choice.

Results

Analysis of Mesh Pad Soil Displacement Data

Average daily displacement in control fields was 0.033 kg/m^2. (95% CI [0.027, 0.038]). Model results showed that the treatment effect is 0.67, or a 33% reduction in in-field soil erosion (Table 2). For comparison, a fixed effect model lm1 was constructed with the lm function from the stats package in R (R Core Team, 2018; documentation at https://stat.ethz.ch/R-manual/R-devel/library/stats/html/00Index.html). Site is treated as a fixed effect, and all other parameters are identical to those in lmer1 (Table 2).

Table 2: Estimate of Treatment Effect with lmer1 and lm1 Model. The two models are identical, except for the site covariate. In lmer1, site is treated as a random effect, and in lm1 it is treated as a fixed effect. Estimate of treatment effect is multiplicative, meaning that erosion on a prairie treatment site is estimated at 67% of the erosion on a control site.

Model	Estimate of Treatment Effect	SE	df	T-ratio	p-value	Lower CL	Upper CL
lmer1	0.67	1.10	164.55	-4.164	1e-04	0.56	0.81
lm1	0.67	1.10	165	-4.168	<0.0001	0.56	0.81

Next, a type III test was conducted to obtain F Values for the fixed effects of the lmer1 model (Table 3).

Table 3: Type III Wald F tests with Kenward-Roger df for lmer1 Model

	F	Df	Df.res	Pr(>F)	Significance
Treatment	17.3424	1	165.02	5.019e-05	***
Year	19.1180	2	153.69	3.849e-08	***
Survey	2.0004	2	166.81	0.1385	
Position	2.9816	2	165.02	0.0535	.
Crop	3.1829	1	167.77	0.0762	.

Significance codes: *** = p<0.001; ** = p<0.01; * = p<0.05; . = p<0.1

Treatment and year were highly significant (p= 0.001), while crop and position were marginally significant (p= 0.10). The variance component of site, the random effect, was 0.78, compared to the residual variance component of 0.40, indicating that there is more variability among treatments that can be accounted for by site than variability among treatments that cannot be accounted for. Output in R for all tests is found in Appendix F.

An exploratory model, lmer3, was also run to investigate potential interaction effects between treatment and position (see Appendix F for construction). The intent of this model was to determine the extent to which erosion differs at various sections down the hillslope based on treatment with prairie. The treatment:position interaction is not significant (Table 4). The exploratory model also incorporates interaction effects between site, treatment, and survey to adjust for conditions that vary by location and sampling date, which may influence the effectiveness of strips. Table 4 also shows the significance of the fixed effects in this model, and Table 5 shows the variance components of the random effects.

Table 4: Results of Fixed Effects in the Exploratory Model.

	F	Df	Df.res	Pr(>F)	Significance
Treatment	6.8157	1	13.347	0.0212	*
Position	2.1879	2	137.149	0.1161	
Year	36.0879	2	147.790	1.728e-13	***
Survey	0.4041	2	10.299	0.6777	
Treatment:Position	0.5945	2	137.149	0.5533	

Significance codes: *** = p<0.001; ** = p<0.01; * = p<0.05; . = p<0.1

The interaction of site:treatment:survey has a variance component of zero, so it does not account for any variability within the data. The site:survey interaction and site effect have a variance component that is larger than that of the residual, which is to be expected. The relatively large variance component of the site effect supports the idea that many conditions that can influence erosion, such as topography, soil type, and rainfall, vary among properties. The variance component of site:survey supports the idea that regional variability in climate can lead to regional differences in erosion during a given survey window.

Table 5: Significance of Random Effects in Exploratory Model. Most variability can be accounted for with the listed effects. Site, the site:survey interaction, and the site:treatment interaction are all responsible for some amount of variation in the data, with site responsible for much of the variation.

	Variance	Std. Dev.
Site:Treatment:Survey	0.00	0.00
Site:Survey	0.29	0.54
Site:Treatment	0.06	0.24
Site	0.63	0.80
Residual	0.25	0.50

There is also a small variance component associated with the site:treatment interaction effect. The interpretation of this effect may be that treatment is more effective at some properties than at others. Further studies could shed light on this possibility and the conditions that improve or impair prairie strip performance. The results of soil displacement by site underscore the variability of prairie strip effectiveness from farm to farm in terms of erosion control (Fig. 1).

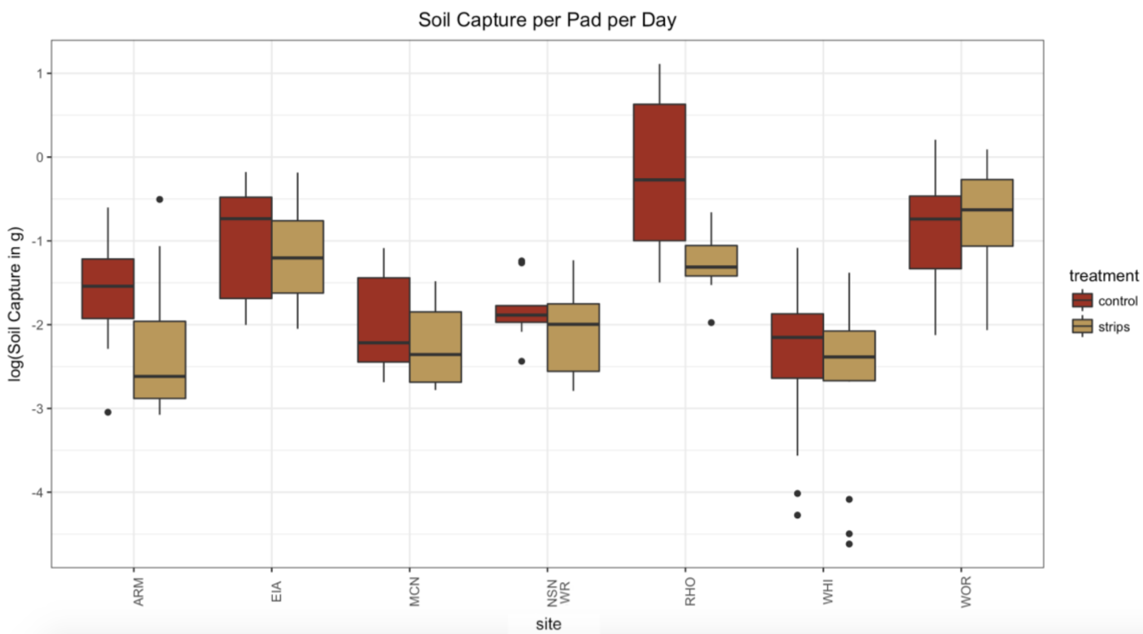


Figure 1: Erosion by Site and Treatment in Exploratory lmer3 Model. Each site is represented by a three-letter code, with NSNWR at the center. The box plots show the 25th, 50th, and 75th percentile of soil capture per mesh pad, with lines reaching the 0th and 100th percentile, and dots denote outliers.

Initial WEPP Runs to Ascertain Effect on Sediment Yield

The default settings in WEPP, without any parametrizing to improve model fit to field data, confirm that prairie strips can decrease sedimentation, as seen in Table 6.

Table 6: Results of Initial WEPP Simulations, in comparison to observed empirical results. Data are presented as the mean (over all three watersheds in each treatment group) of the average annual sediment delivery, runoff, and displacement. Runoff is presented in mm, in the same units as precipitation. Average annual runoff of 96 mm in a watershed with 960 mm average annual precipitation means that 10% of the precipitation runs off the watershed. A value of 1 mm corresponds to 10 m^3 per hectare, or 10,000 L per hectare of average annual runoff by volume.

	WEPP Mean Sediment (Mg/ha)	Empirical Mean Sediment (Mg/ha)	WEPP Mean Runoff (mm)	Empirical Mean Runoff (mm)	WEPP Mean Displacement (kg/m^2)
20% Prairie in Contour Strips and at Footslope	2.85 ± 0.65	0.30 ± 0.16	96.12 ± 1.3	114.8 ± 41.0	0.39 ± 0.22
10% Prairie in Contour Strips and at Footslope	3.33 ± 0.49	0.25 ± 0.06	92.2 ± 13.3	108.4 ± 24.9	0.63 ± 0.17
10% Prairie at Footslope	3.10 ± 0.40	0.20 ± 0.08	101.5 ± 9.1	66.2 ± 7.5	0.56 ± 0.19
100% Row-crop	11.33 ± 1.31	5.36 ± 1.59	123.6 ± 6.3	169.3 ± 41.8	1.13 ± 0.23

On-Site and Off-Site Results of Calibrated WEPP Simulations

The results of the calibrated WEPP simulations on sedimentation, in-field soil displacement, and runoff are included below and compared to empirical results.

In-Field Soil Displacement

As in-field soil displacement data are only available for the NSNWR watersheds in the year 2015, they were not compared pairwise with WEPP predictions. However, a brief summary of in-field soil displacement is included in Table 7.

Table 7: WEPP Prediction of Average In-Field Soil Displacement

Field Type	WEPP Prediction of Average In-Field Soil Displacement (kg/m^2)
All Row-crop	1.13
10% prairie at footslope	0.42
10% prairie at footslope and in contour strips	0.53
20% prairie at footslope and in contour strips	0.37

The data for Table 7 were taken directly from WEPP simulation results. However, the data format is not directly comparable to results from the mesh pad experiment from Part One, so additional adjustment was required. While the WEPP simulation averages displacement over the full area of the slope, including areas in prairie strips, the mesh pad data described in this paper only monitored displacement in the crop area. This difference was adjusted for by dividing the simulated soil displacement in fields with 10% and 20% prairie by 0.9 and 0.8, respectively, and calculating the mean displacement in kg/ha row-crop area. After this adjustment, the estimated reduction in soil displacement in treatment fields compared to control fields is 55%, which is still somewhat greater than the 33% reduction that was modeled using the mesh pad data.

Sediment Delivery

WEPP sediment outputs were compared to empirical values for each watershed, expressed as the annual average of cumulative sediment export for the years 2007 to 2014. Figure 2 shows the relationship between sediment delivery calculated from H-flume concentrations and that predicted in WEPP simulations. Data are represented on log scale, with the unit line y=x included as a reference. Sites with prairie are clustered in the lower left quadrant, and 100% row-crop sites are clustered in the upper right quadrant, showing that the model is able to distinguish the effect of prairie treatment. Both clusters intersect the line y=x, indicating that the model is a relatively accurate fit, although many points occur above y=x, which suggests that the model overestimates sedimentation on most sites.

As can be observed in Figure 3, the prairie simulations came much closer to the actual H-flume values than did the row-crop simulations. For the 10% contour and footslope prairie sites and 20% contour and footslope and prairie sites, the WEPP and H-flume estimates were not statistically different, as the error bars overlap.

However, in the 100% row-crop fields there was considerable variability from year to year in the sediment delivery observed. For instance, watershed B6 averaged over 24,700 kg/ha in 2008, but only 140 kg/ha in 2007 (Appendix E). Furthermore, much of this erosion occurs during a few events. The example in Figures 4 and 5 shows daily erosion, expressed as kg per meter of width, on hillslopes B4 (with prairie) and B6 (without prairie). On slope B6, the sediment export is dominated by one particular rainfall event around Julian day 1300. On slope B4, the sediment export from this event has been moderated by the prairie strips, bringing the sediment close to that observed during other more minor events. Many of these sediment delivery events correspond to relatively high levels of precipitation (Figure 6). Precipitation intensity in mm/h is also related to sediment delivery to a lesser extent, as seen in Figure 7. This indicates that both sediment delivery and WEPP predictions may be particularly volatile during extreme weather events, especially in the absence of the protective cover of perennial vegetation such as prairie strips.

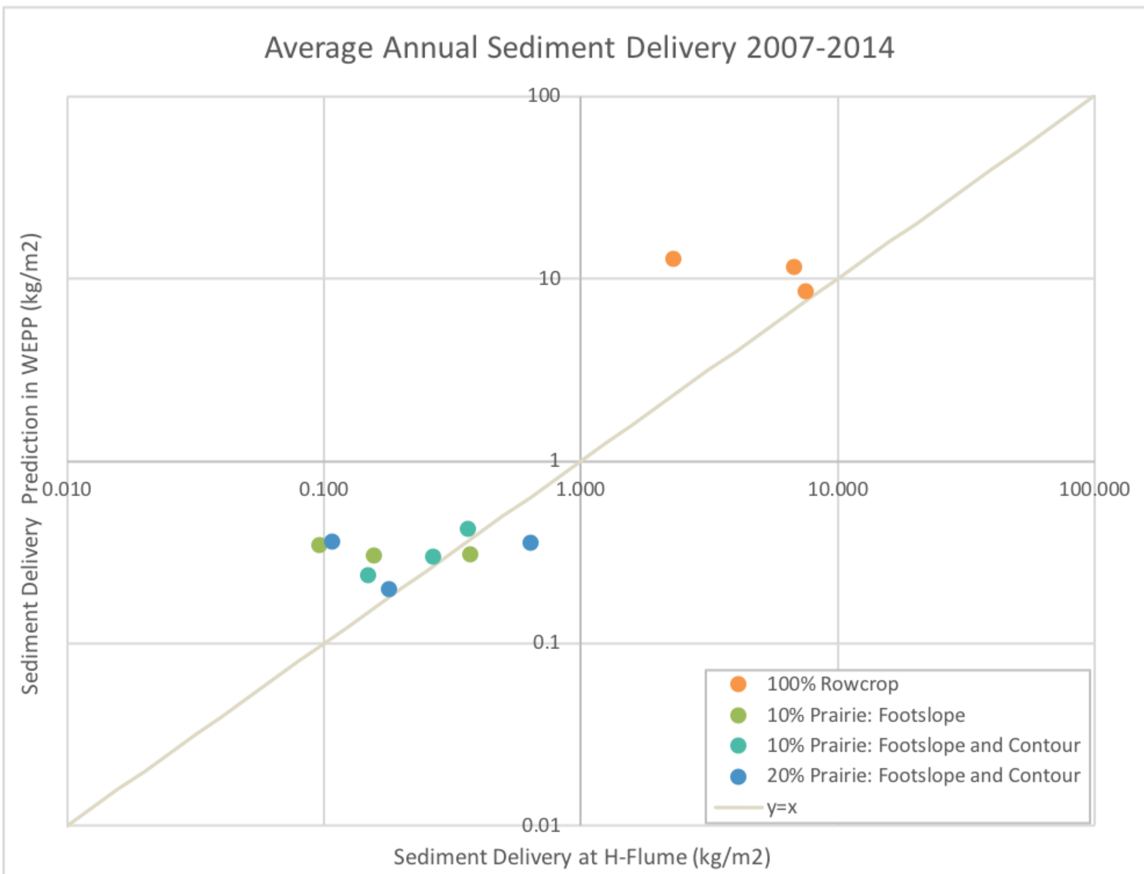
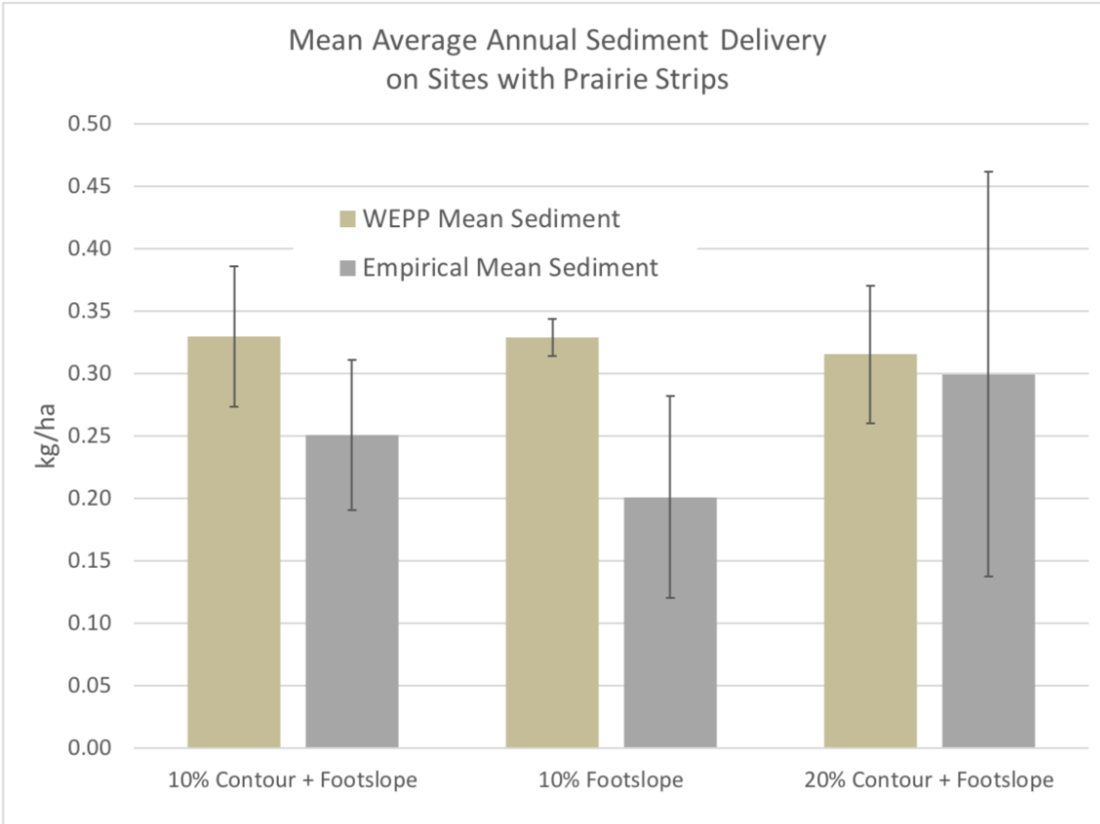
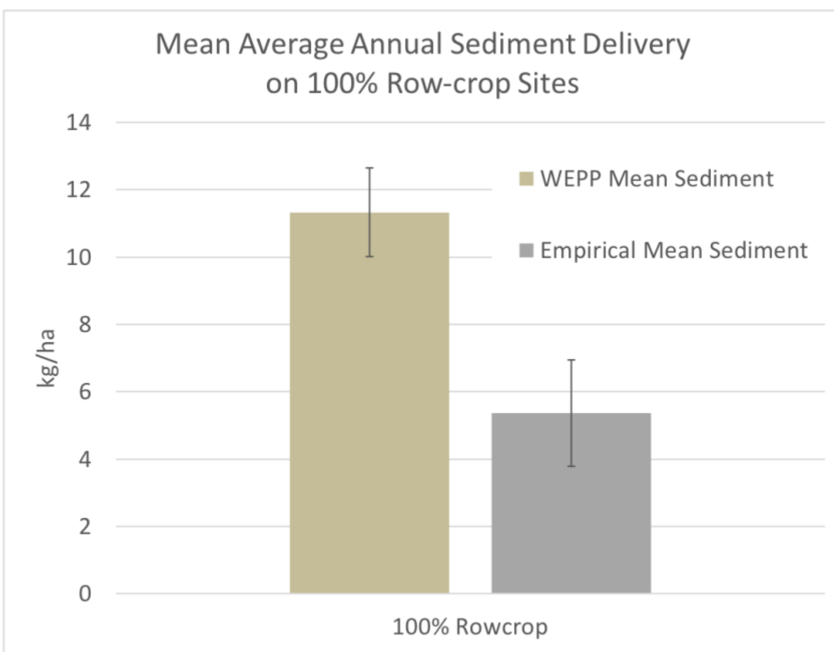


Figure 2: Observed Average Annual Sediment Delivery 2007-2014 (H-flume), in comparison with the Predicted Sediment Delivery. Green and blue colors represent treatment fields with prairie integration, and orange represents control fields with 100% row-crop.



a)



b)

Figure 3: Comparison of Mean Average (+ Standard Error) Annual Sediment Delivery with WEPP and H-flume Data. Figure 3a shows sediment delivery on treatment sites with three configurations of prairie strips, while 3b shows sediment delivery on 100% row-crop sites.

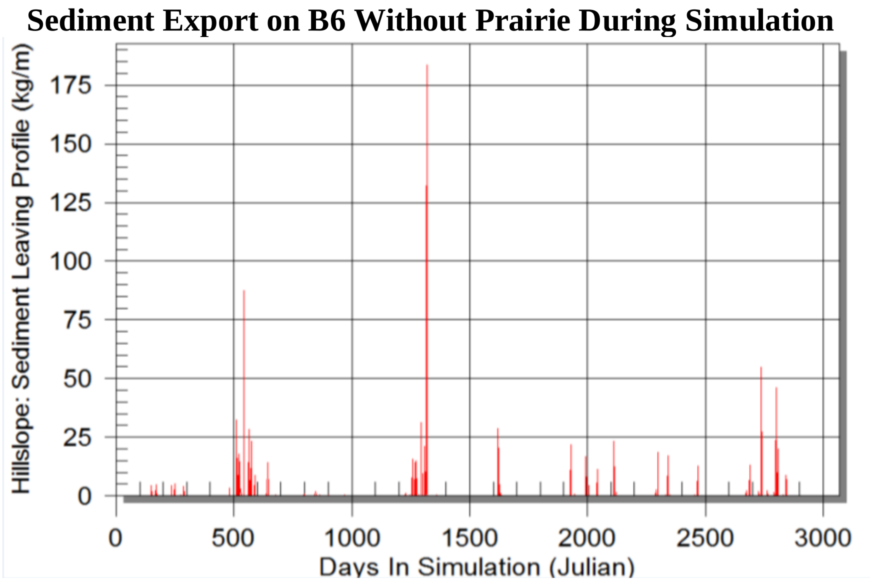


Figure 4: Daily Sediment Delivery in 100% Row-crop (B6) WEPP Simulation. The high-intensity event is visible near Julian Day 1300, which eclipses all other events.

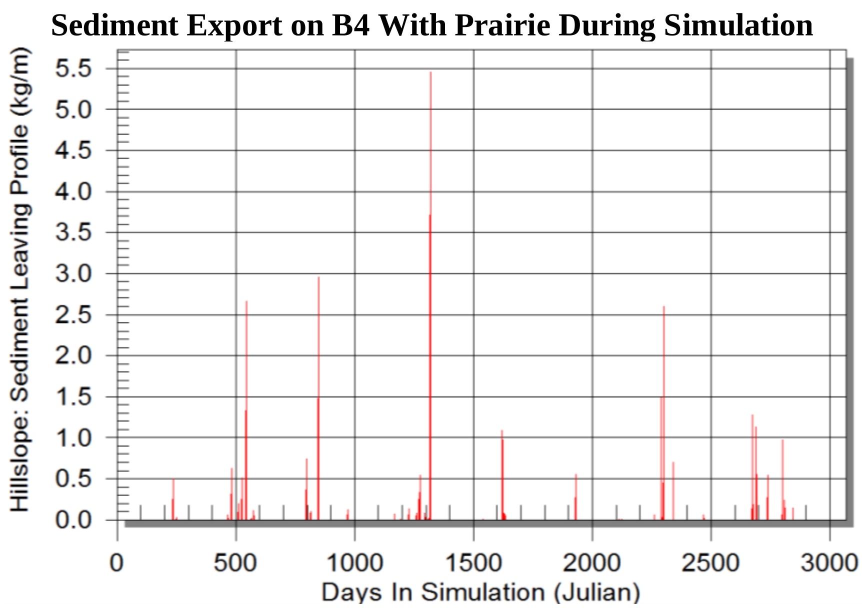


Figure 5: Daily Sediment Delivery in 20% Prairie (B4) WEPP Simulation. Erosion from the event around Julian Day 1300 is decreased and is closer in value to peak periods of sedimentation during several other events, such as those around Julian Days 550, 850, 1625, 2300, 2700, and 2800.

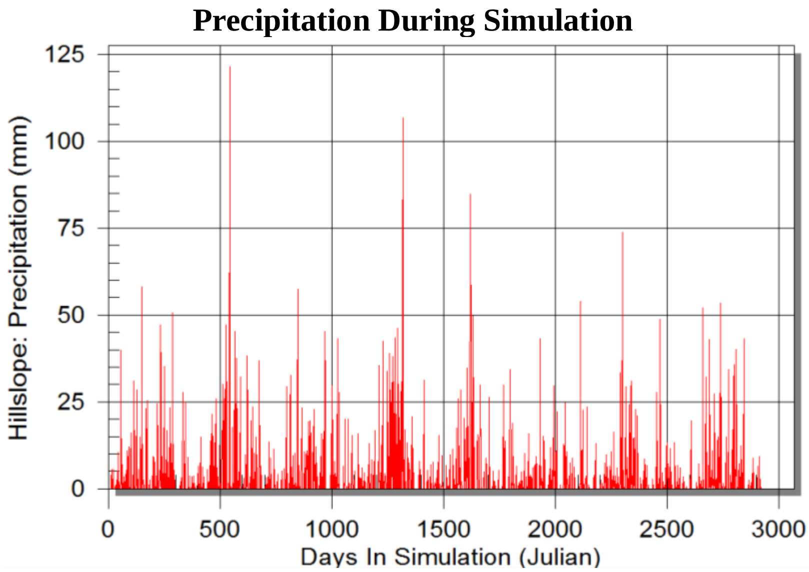


Figure 6: Daily Precipitation at NSNWR 2007-2014 used for simulation. Peaks in precipitation show high-intensity rainfall events, many of which correspond to periods of high sediment delivery in Figure 5, around Julian Days 550, 850, 1300, 1625, 2300, 2700, and 2800. The annual pattern of rainy season and dry season is also visible as a scalloped pattern with periods of high precipitation followed by periods of lower precipitation.

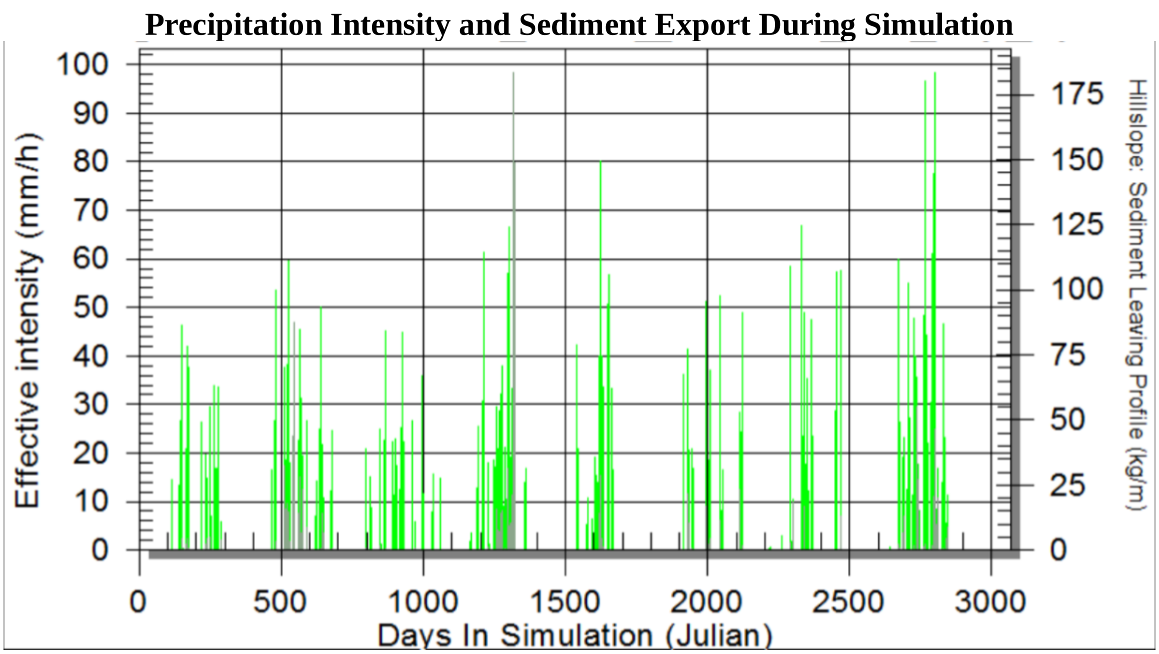


Figure 7: Precipitation Intensity and Sediment Export on 100% Row-crop Slope. Intensity is in bright green, and sediment is in dark green. An annual pattern of rainy season and dry season is visible, with periods of high rainfall intensity followed by periods of lower intensity.

Next, a simple linear model was constructed to determine the effect of prairie strip treatment on sediment delivery. The points were categorized into one of two groups: "Control," consisting solely of the 100% row-crop fields, and "Strips," consisting of all fields containing 10% or 20% prairie at the footslope and/or in contour strips. According to the WEPP simulation results, prairie strip treatment decreased sediment export by an estimated 97.16%. In comparison, prairie strips decreased erosion by 95.60% according to H-flume data (Fig 8). The full R script outputs can be found in Appendix F.

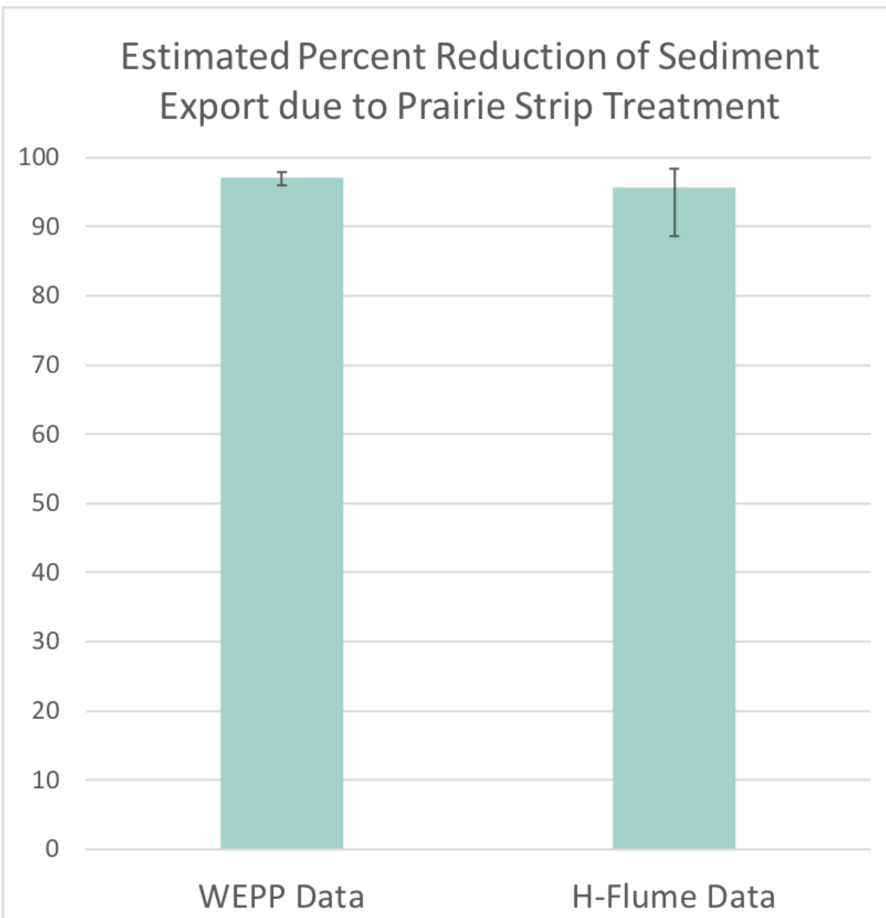


Figure 8: Estimated Percent Reduction of Sediment Export due to Prairie Strip Treatment: Comparison of Simulated and Empirical Data. These are the results of the two linear models constructed to determine the effect of prairie strips on reducing sediment

export. The vertical lines show the upper and lower bound of the 95% confidence interval. Both results are significantly different from 100% row-crop control fields ($p<0.0001$. There is no significant difference between the estimated percent reduction using the WEPP method versus the H-flume method.

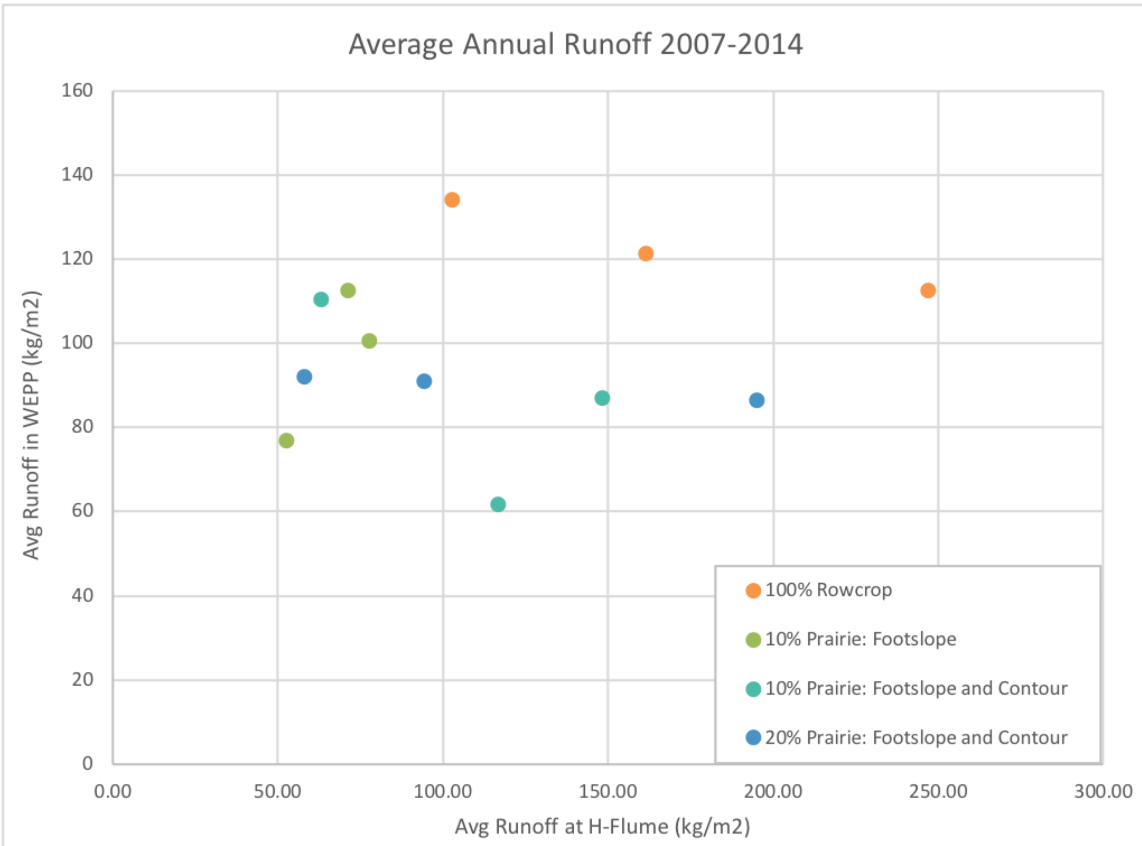


Figure 9: Observed Average Annual Runoff 2007-2014, in comparison with Predicted Runoff. Each point represents one watershed, with simulated runoff plotted against empirical runoff. Green and blue colors represent treatment fields with prairie integration, orange represents control fields with 100% row-crop.

Runoff

WEPP runoff outputs were compared to empirical values, expressed as the annual average of cumulative runoff from 2007-2014 (Fig. 9). There is a slight trend toward less runoff for watersheds with prairie, although this trend is more pronounced in simulations than in empirical data. This could indicate that there are additional factors that affect runoff even in similar watersheds, which this model did not fully capture. There is also considerable variability in runoff between treatments, as well as in the difference between prediction and empirical measurement. No clear trend in over- or under-prediction is apparent in the simulations.

The mean average annual runoff for each treatment type shows a tendency in which runoff is decreased on fields with prairie installations, and in which empirical mean runoff is (with one exception) higher than that of WEPP (Fig. 10).

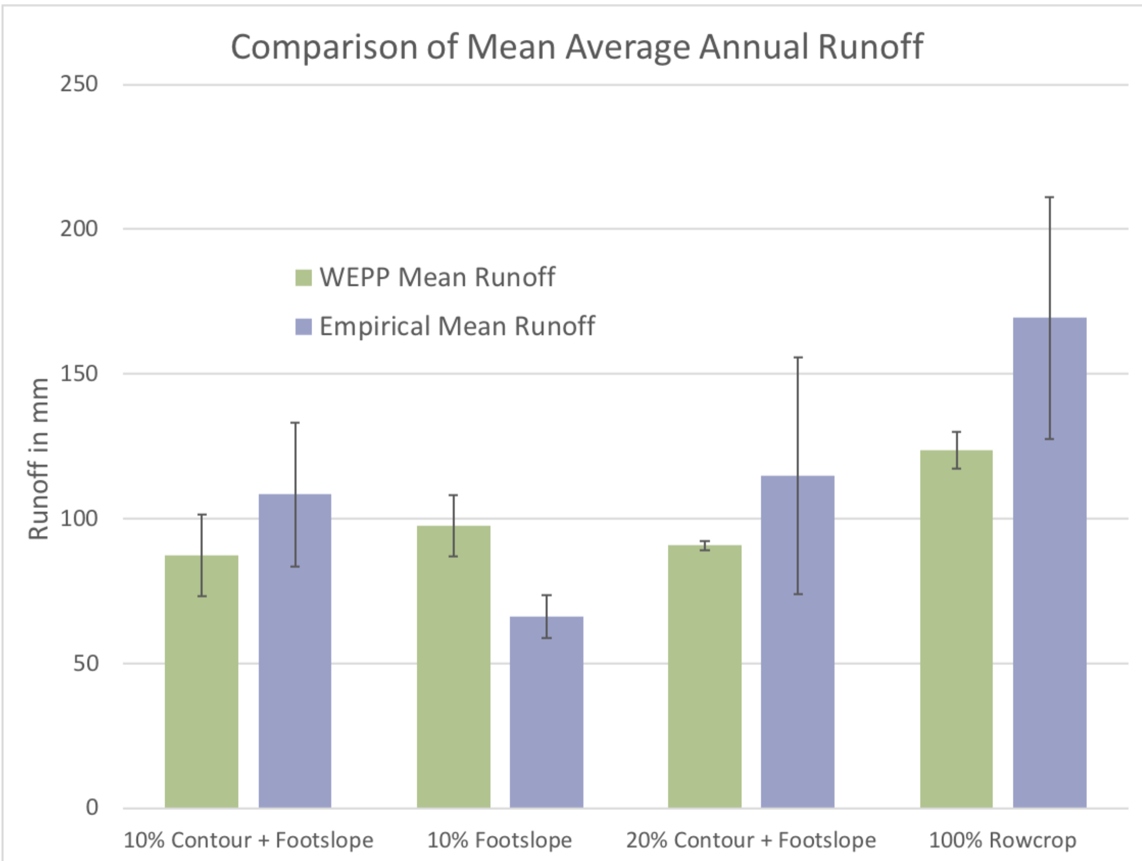


Figure 10: Comparison of Mean Average Annual Runoff on Sites with Prairie Strips with WEPP and H-Flume Data. Error bars indicating standard error are especially wide for empirical data, showing high variability between sites. Error bars from WEPP and empirical H-flume data overlap in each category, with one exception, suggesting a good model fit. With one exception, runoff also appears to be higher for empirical data than for WEPP simulations, potentially indicating that the simulations underestimate runoff.

A linear model was then constructed to determine the effect of prairie strip treatment on runoff. As in the sediment delivery model, the points were sorted into one of two categories: “Control,” consisting solely of the 100% row-crop fields, and “Treatment,” consisting of all fields containing 10% or 20% prairie at the footslope and/or in contour strips.

In contrast to the sediment delivery model, however, the runoff model appears to underestimate the capacity of prairie strips to control runoff. Due to high variability of the data, confidence intervals are wide. WEPP simulations indicate a 27% decrease (95% CI [6%, 43%]; p=0.0206) in runoff on slopes with strips compared to slopes with only row-crops. H-flume data indicates a 45% decrease (95% CI [72%, 108%]) in runoff on slopes with strips compared to only row-crops, although the effect is not statistically significant (p=0.075).

Side-by-Side Comparison with Empirical Data

A summary of average annual sediment, runoff, and displacement data from the twelve watersheds shows that on sites with prairie strips, sediment delivery is reduced by over an order of magnitude, and soil displacement and runoff are also reduced (Table 8). Table 9 shows the same results, aggregated by treatment type. WEPP simulations tend to overestimate sediment export but are generally consistent with empirical results, especially for watersheds with prairie strips. This indicates that prairie strip treatment is an effective soil and water conservation measure on row-crop fields, and that WEPP has potential as a predictor of the soil and water benefits of prairie strip installation.

Table 8: Comparison of Simulated and Empirical Averages of Sediment, Runoff, and Displacement. Average precipitation for the 8-year period was 966.07 mm. Sediment delivery, runoff, and soil displacement are reduced on sites with prairie strip treatment. WEPP results have a tendency to overpredict sediment export, but track empirical trends.

		WEPP			EMPIRICAL	
Site	Location and % Prairie	Sediment in Mg/ha	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha	Runoff in mm
B1	10% at footslope	0.36	101.4	0.32	0.09	76.7
B2	5% at footslope and 5% at upslope	0.31	87.9	0.38	0.26	147.3
B3	10% at footslope and 10% at upslope	0.37	91.9	0.35	0.10	93.3
B4	10% at footslope and 10% at upslope	0.37	87.3	0.63	0.62	194.0
B5	5% at footslope and 5% at upslope	0.25	62.6	0.64	0.14	115.8
B6	All row-crops	11.92	113.5	1.19	6.58	245.9
I1	3.3% at footslope, 3.3% at sideslope, and 3.3% at upslope	0.44	111.4	0.58	0.35	62.1
I2	10% at footslope	0.32	113.5	0.32	0.36	70.2
I3	All row-crops	8.83	122.3	0.88	7.29	160.3
O1	10% at footslope	0.31	77.6	0.62	0.15	51.6
O2	6.7% at footslope, 6.7% at sideslope, and 6.7% at upslope	0.21	92.8	0.14	0.17	57.0
O3	All row-crops	13.23	135.0	1.32	2.21	101.8

Table 9: Mean Sediment and Runoff by Treatment. While Table 6 presented soil and water outputs for the uncalibrated model, Table 9 presents soil and water outputs for the calibrated model, for which prairie land cover factors were adjusted. Since no row-crop parameters were calibrated, the 100% row-crop results are identical in both tables. Empirical data from the H-flumes is included for reference and is also identical in both tables.

	WEPP Mean Sediment (Mg/ha)	Empirical Mean Sediment (Mg/ha)	WEPP Mean Runoff (mm)	Empirical Mean Runoff (mm)	WEPP Mean Displacement (kg/m^2)
20% Prairie in Contour Strips and at Footslope	0.32 ± 0.06	0.30 ± 0.16	90.7 ± 1.7	114.8 ± 41.0	0.37 ± 0.14
10% Prairie in Contour Strips and at Footslope	0.33 ± 0.06	0.25 ± 0.06	87.3 ± 14.1	108.4 ± 24.9	0.53 ± 0.08
10% Prairie at Footslope	0.33 ± 0.02	0.20 ± 0.08	97.5 ± 10.5	66.2 ± 7.5	0.42 ± 0.10
100% Row-crop	11.33 ± 1.31	5.36 ± 1.59	123.6 ± 6.3	169.3 ± 41.8	1.13 ± 0.23

Sensitivity Analysis

The results of the sensitivity analyses on plant choice, biomass value, and slope profile choice suggest that the model is robust with regard to prairie plant database choice (Table 10), and more sensitive with respect to slope transect choice (Table 11) and prairie BEINP value (Table 12).

Table 10 summarizes the effect of prairie plant database choice on runoff, displacement, and sediment export. The “Good Kansas,” “Fair Kansas,” and “Fair Nebraska” files represent good or fair ecological quality bluestem prairie calibrated during experiments in Kansas or Nebraska, respectively. The four adjustments used in the main analysis (Darcy–Weisbach, plant spacing, base daily air temperature, and BEINP) were made to each plant choice file before running the sensitivity analysis simulations. Results for each watershed are consistent as the prairie database file is changed, indicating that other plant parameter differences between the three database files are not driving variables in the model (Table 10).

Table 11 shows results for each watershed with four different watershed transects: two transects that travel smoothly down the face of the watershed (Table 11a) and two that follow a gully or lowest-elevation path (Table 11b). There does not appear to be a strong trend for any of the outputs with regard to slope transect choice, although often displacement and sediment appear to be slightly decreased on gully transects (Table 11b). Variability in runoff tends to be less than a few percent, while variability in sediment and displacement is somewhat greater (Tables 11a and 11b). For a small number of data points, slope file choice had a significant effect: a notable example is O3 Gully Transect 1, for which displacement and sediment are substantially increased (Table 11b).

Sediment yield appears to vary inversely with BEINP value, and runoff also appears to decrease slightly as BEINP increases (Table 12). There is no clear trend for soil displacement as a function of BEINP, although on some watersheds displacement decreases slightly as BEINP increases (Table 12).

Table 10: Sensitivity Analysis: Prairie Plant Database Choice on WEPP Outputs for Prairie-Rowcrop Sites. Each row in the table represents one watershed. Three prairie plant database files from the WEPP rangeland input file collection are compared side by side. As 100% row-crop sites (B6, I3, O3) include no prairie, and thus prairie plant choice has no impact on outputs, those sites are excluded from the table.

	Good Kansas (used in main analysis)			Fair Kansas			Fair Nebraska		
Site	Runoff in mm	Displace-ment in kg/m^2	Sediment in Mg/ha	Runoff in mm	Displace-ment in kg/m^2	Sediment in Mg/ha	Runoff in mm	Displace-ment in kg/m^2	Sediment in Mg/ha
B1	101.4	0.32	0.36	101.4	0.32	0.36	101.3	0.32	0.36
B2	87.9	0.38	0.31	87.8	0.38	0.31	87.8	0.38	0.31
B3	91.9	0.35	0.37	91.9	0.35	0.37	91.9	0.35	0.37
B4	87.3	0.63	0.37	87.4	0.63	0.37	87.3	0.63	0.37
B5	62.6	0.64	0.25	62.6	0.65	0.25	62.6	0.65	0.25
I1	111.4	0.58	0.44	111.3	0.58	0.44	111.3	0.58	0.44
I2	113.5	0.32	0.32	113.4	0.32	0.32	113.6	0.32	0.32
O1	77.6	0.62	0.31	77.7	0.62	0.31	77.6	0.62	0.31
O2	92.8	0.14	0.21	93.0	0.14	0.20	92.9	0.14	0.21

Table 11a: Sensitivity Analysis: Slope Transect Choice on WEPP Outputs (Slope Face Transects). Each row represents one watershed site. Four slope transects are compared, which were derived from ArcGIS as described in the Methods section. The slope face transects approximate the most realistic path of a water droplet traveling from the hilltop down the face of the slope to the footslope that is possible without falling into a central channel or gully.

		Slope Face Transect 1 (used in main analysis)			Slope Face Transect 2		
Site	Location and % Prairie	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha
B1	10% at footslope	101.4	0.32	0.36	101.2	0.37	0.39
B2	5% at footslope and 5% at upslope	89.4	0.16	0.32	88.4	0.17	0.32
B3	10% at footslope and 10% at upslope	91.9	0.35	0.37	89.3	0.34	0.34
B4	10% at footslope and 10% at upslope	87.3	0.63	0.37	87.5	0.48	0.40
B5	5% at footslope and 5% at upslope	62.6	0.64	0.25	63.3	0.71	0.26
B6	All row-crops	113.5	1.19	11.92	109.6	1.24	12.41
I1	3.3% at footslope, 3.3% at sideslope, and 3.3% at upslope	111.4	0.58	0.44	111.1	0.49	0.34
I2	10% at footslope	113.5	0.32	0.32	114.0	0.39	0.27
I3	All row-crops	122.3	0.88	8.83	127.8	0.77	7.67
O1	10% at footslope	77.6	0.62	0.31	77.4	0.66	0.20
O2	6.7% at footslope, 6.7% at sideslope, and 6.7% at upslope	92.8	0.14	0.21	93.2	0.23	0.24
O3	All row-crops	135.0	1.32	13.23	135.2	1.44	14.38

Table 11b: Sensitivity Analysis: Slope Transect Choice on WEPP Outputs (Gully Transects). Each row represents one watershed site. Four slope transects are compared, which were derived from ArcGIS as described in the Methods section. The gully transects follow the lowest-elevation channel from the upper rim of the watershed to the toeslope.

		Gully Transect 1			Gully Transect 2		
Site	Location and % Prairie	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha
B1	10% at footslope	100.6	0.22	0.34	100.1	0.20	0.32
B2	5% at footslope and 5% at upslope	88.9	0.15	0.30	88.6	0.17	0.31
B3	10% at footslope and 10% at upslope	91.4	0.31	0.36	88.6	0.33	0.32
B4	10% at footslope and 10% at upslope	87.8	0.63	0.38	88.4	0.61	0.39
B5	5% at footslope and 5% at upslope	62.2	0.65	0.21	63.2	0.71	0.26
B6	All row-crops	109.6	1.02	10.17	109.1	1.26	12.57
I1	3.3% at footslope, 3.3% at sideslope, and 3.3% at upslope	110.8	0.56	0.33	110.7	0.49	0.32
I2	10% at footslope	113.1	0.23	0.31	113.1	0.24	0.26
I3	All row-crops	126.6	0.70	6.99	129.1	0.66	6.60
O1	10% at footslope	77.3	0.40	0.14	77.9	0.47	0.14
O2	6.7% at footslope, 6.7% at sideslope, and 6.7% at upslope	92.9	0.13	0.20	92.9	0.18	0.20
O3	All row-crops	132.3	1.77	17.69	134.7	1.17	11.69

Table 12: Sensitivity Analysis: Biomass Energy Ratio on WEPP Outputs for Prairie-Rowcrop Sites. Biomass Energy Ratio, or BEINP, was calibrated to produce an appropriate quantity of live biomass in simulated prairie areas. Three BEINP values are used in this sensitivity analysis to determine its impact on simulated runoff, displacement, and sediment deliver. As discussed in Appendix D, a BEINP of 16 corresponds to a conservative estimate of live biomass for established strips. A BEINP of 20 kg/MJ represents a high estimate, comparable to the most productive established strips sites. A BEINP of 12 kg/MJ is a low estimate, producing live biomass values on par with those seen in first-year strips. Each row in the table represents a row-crop-prairie watershed site; 100% row-crop sites are excluded from this analysis.

	BEINP = 12 kg/MJ			BEINP = 16 kg/MJ (used in main analysis)			BEINP = 20 kg/MJ		
Site	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha	Runoff in mm	Displacement in kg/m^2	Sediment in Mg/ha
B1	102.4	0.40	0.41	101.4	0.32	0.36	100.9	0.42	0.36
B2	90.2	0.17	0.36	89.4	0.16	0.32	89.1	0.17	0.31
B3	93.8	0.35	0.44	91.9	0.35	0.37	91.9	0.35	0.36
B4	88.9	0.65	0.47	87.3	0.63	0.37	86.9	0.62	0.35
B5	63.7	0.65	0.29	62.6	0.64	0.25	62.6	0.63	0.23
I1	112.2	0.58	0.47	111.4	0.58	0.44	110.9	0.58	0.43
I2	113.9	0.34	0.35	113.5	0.32	0.32	113.5	0.30	0.29
O1	78.5	0.54	0.35	77.6	0.62	0.31	77.7	0.58	0.30
O2	93.6	0.14	0.23	92.8	0.14	0.21	92.9	0.14	0.18

Discussion

Primary Findings and Implications

The first overarching question guiding this research was whether prairie strips improve soil and water retention on annual crop fields. Overall, my results confirm the disproportionate benefits of prairie strips on soil export, displacement, and runoff compared to the extent of their planting (10–20% of the crop field), adding to the body of evidence on the ecosystem services provided by prairie strips (Schulte et al., 2017). The other overarching question was how model-based estimates compared with empirical data, and results are promising. The similarity between the simulated versus empirical effects of treatment confirms the potential to use WEPP to predict the benefits of new prairie strip installations.

The use of longer-term data sets and the combination of simulation modeling and analysis of empirical field measurements adds robust support to the conclusions of Helmers et al. (2012), that prairie strip technology reduces sediment export by well over 90% and also appears to reduce runoff. Furthermore, my results over eight years also indicate a maintained comparative advantage of prairie strips as no-till systems continue to mature, a question posed in the discussion of Helmers et al., 2012. My findings also confirm the conclusion of Helmers et al. (2012) that there is no significant difference in sediment export between fields with 20% prairie cover and those with 10%, indicating that 10% prairie strip integration on corn and soybean fields is an effective strategy for keeping soil from moving on Midwest farmland. In addition, prairie strip integration reduces sediment export to well below the NRCS's T-value of 5 short tons per acre or

11.2 Mg/ha, the maximum "tolerable" level of annual erosion required for sustaining soil resources over the long-term.

Because of its flexibility, user-friendly interface, extensive pre-existing parameter database, and suitability for long-term predictions, the WEPP modeling in this research represents an important, complementary capability to the single event model of row-crop-prairie systems pioneered by Luquin Oroz (2016). While the LISEM model used by Luquin Oroz is powerful and highly accurate, it depends on extensive, site-specific data collection that may be inaccessible or impractical for farmers and prairie consultants interested in conservation. The comparability of WEPP soil and water outputs to collected sediment, runoff, and in-field displacement data over a multi-year time period is especially promising for the model's potential to inform farmer decisions and predict long-term impact of prairie strip technology.

This research also confirms the results of initial experimentation with WEPP modeling of row-crop-prairie systems by Gesell (2017), and makes a number of strides in improving predictions and informing future methodology. On sites I1, I2, and I3, Gesell (2017) found decreased sediment export on the sites that included prairie land cover. In this full-scale study, the addition of custom-built slope files, soil profiles generated from ArcGIS shapefiles, empirical climate data, and calibration of prairie plant data files led to much improved accuracy.

Initial runs before calibration confirmed the potential of prairie strips to decrease sediment export, therefore answering the question posed in the "Objectives" section about WEPP's prediction of decreased sedimentation in row-crop-prairie areas. In the initial runs, however, this effect was underestimated in comparison to empirical data.

Parameterization of key factors improved these predictions significantly: sediment export predictions in WEPP after calibration are close to real calculations on the field for sites with prairie integration both in terms of raw amount and in terms of multiplicative effect. Although simulations for sites with 100% row-crop cover are highly variable, they mirror physical phenomena occurring in these fields under extreme precipitation events.

Calibration of the WEPP model revealed a number of important adjustments and considerations that are necessary for more consistent and accurate predictions, several of which are described in greater detail in the Appendices. A summary of these is included below:

Table 13: Summary of Simulation Parameterization

Parameter	**Assumption/Recommendation**
Darcy–Weisbach Minimum Friction Factor (Prairie)	136. The model is highly sensitive to this parameter.
BEINP (Prairie)	16 kg/MJ for established strips. The model is moderately sensitive to this parameter.
Base Daily Air Temperature (Prairie)	4.4°F
Prairie Land Cover Template File	Bluestem Prairie, good condition (KS)
Plant Spacing (Prairie)	Not a driving parameter. This study uses a spacing of 0.5 cm.

Crop rotation	Make sure the corn-soybean rotation starts on the proper year
Slope file	Use Interpolate Line in the ArcGIS Spatial Analyst toolbox to generate a representative profile (not a gully). Points in SLP file should be no closer than 5 m apart.
Climate	Use real climate data
Soil	Use SSURGO soil data, approximate in ArcGIS
Land cover	Use watershed polygons if available, approximate length in ArcGIS
Snow Melt	Potentially underpredicted for Year 1

The substantial effect of prairie integration on sediment export does not significantly differ between WEPP and H-flume data, as indicated by the concentric confidence intervals, indicating a good model fit. As seen in the results, WEPP overestimates sediment export, especially in highly erodible 100% row-crop scenarios, which may contribute to its slight overestimation of the treatment effect. These results are also logical in light of prior studies that found the WEPP model estimated reduction in sedimentation with the use of other conservation practices, such as grass buffer strips, on Midwestern agricultural watersheds (Zhou et al., 2009; Das et al., 2004). The modeled effect of perennial prairie vegetation appears to be significantly greater than that of typical Conservation Reserve Program-type grass buffer strips, which Das et al. (2004) estimated led to a 48.2% reduction in sedimentation.

In addition, both WEPP simulations and H-flume data spanning 2007-2014 predict decreased runoff in row-crop-prairie systems, and the confidence intervals are once again concentric, indicating that the simulations are a good fit. Consistent with the findings of Helmers et al. (2012), variability in the data was high, and confidence intervals wide. Resultingly, as in the Helmers et al. study, one data set indicated a statistically significant effect, while the other did not. The high variability of runoff observed in this study is also consistent with observations from other WEPP simulations on Midwestern U.S. agricultural systems (Kirnak, 2001).

Third, prairie strips reduced displacement in the mesh pad experiment conducted on NSNWR and other properties between 2015-2017, thus addressing the question posed in the objectives regarding the ability of prairie strips to reduce in-field erosion. While side-by-side comparison was not conducted for in-field displacement, prairie strips also reduced displacement in the WEPP simulations on NSNWR, although this effect was overestimated in comparison to the mesh pad results. The current study of displacement on fields with prairie integration in particular is important, because it is the first full analysis of multi-year soil pad displacement data in these systems. The collection of mesh pad data is ongoing, which will lead to more refined estimates.

A curious aspect of the WEPP displacement estimates is that the estimated displacement on the slopes with 10% prairie in contours and at the footslope is greater than that on slopes with prairie only at the footslope. We would expect that prairie in contour strips would help slow water flow on lower parts of the hillslope, thus decreasing displacement in comparison slopes that have prairie only at the footslope. However, the range of values observed in each treatment group was comparable, ranging from 0.38 to 0.64 kg/m^2 in the 10% footslope and contour prairie group and ranging from 0.32 to 0.62 kg/m^2 in the 10% footslope prairie only group, in contrast to the 100% row-crop group, which had displacement ranging from 0.88 to 1.32 kg/m^2. The apparent difference between the two 10% prairie treatments is likely only a reflection of the small sample size of each treatment group, with slight variations in size and slope among hillslopes.

I now return to the last component of the Objectives regarding WEPP's utility for farmers. It is apparent from the above that WEPP modeling closely matched empirical data for the multiplicative effect of prairie strips on reducing sedimentation and bore semblance to empirical estimates of sediment export, albeit somewhat overestimated in general. Likewise, the model also predicted reduced runoff and soil displacement on sites with prairie strips, although this effect appears to be underestimated for runoff and overestimated for displacement. Therefore, creating a WEPP simulation of a farmer's property with and without prairie strips would enable a farmer to visualize an approximation of the soil and water benefits this technology would have on their fields, keeping in mind the over- and underestimation biases previously mentioned. Already this would give farmers and landowners a powerful tool to make an informed decision, and further study and calibration will improve its predictive capabilities and ascertain its robustness across different topographies and soils.

With the support of a consultant or university extension, these simulations would be relatively straightforward to create, with the use of publicly available SSURGO soil data; free, open-source GIS software or use of university ArcGIS resources; and creation of a CLIGEN file appropriate for their area or construction of a climate file from publicly available weather station data (NOAA National Centers for Environmental Information, available at https://www.ncdc.noaa.gov/cdo-web/datatools/lcd).

Research suggests that the capabilities of this model align with recommended strategies to increase farmer participation in prairie strip conservation technology. Social science research by J. G. Arbuckle (Arbuckle, 2015) determined that clear presentation of the benefits of prairie strips and inclusion of demonstration sites are two of four potential pathways for widespread adoption. Several farm group interviewees in Arbuckle's analysis emphasized that the long-term benefits and potential for sustainability afforded by conservation measures are compelling to farmers concerned about the continued productivity of their land for future generations. Since WEPP supports multi-year simulations, it would enable farmers to visualize these benefits over a long time frame. Many interviewees highlighted the value of demonstration sites, both as testimonials and motivation by peers as well as sources of "hard…localized data" (Arbuckle, 2015). WEPP simulations could form an effective complement to live demonstration sites of peers, representing a source of localized data customized to their own field.

Additional Considerations

The most important calibrated parameter by far was the Darcy–Weisbach maximum friction factor (FLIVMX). The WEPP user manual recommends a friction factor of 12 for perennial plants; however, using a value of 136 as estimated for an Oklahoma tallgrass prairie in Weltz et al. (1992) gave realistic simulation predictions that matched the effect of prairie treatment on measured sediment delivery. For future row-crop-prairie simulations, it is recommended to begin with a FLIVMX of 136, and then fine-tune with a small calibration dataset.

Two other important issues arose while calibrating the model: the granularity of the slope files and the phase of the corn-soy rotation. As discussed in Appendix A, over-parameterization of slope files caused elevation anomalies that led to unrealistic erosion modeling. For future simulations, it is recommended to format slope files with points no fewer than 5 m apart.

Particularly with shorter simulations such as the 8-year ones conducted in this study, it is important to ensure that the first year of the simulation begins with the appropriate crop. In this case, a new soy-corn rotation file was created to account for the fact that the fields were planted with soybeans in Julian Year One. An example watershed with an out-of-phase crop rotation compared to an in-phase crop rotation can be found in Appendix C.

The sensitivity analysis showed little variability as a result of changing the plant choice type, and moderate variability as a result of changing the slope transect. A slight decrease in sediment delivery and soil displacement was sometimes observed for gully transects, which may result from a smaller total change in elevation along these paths. A dramatic increase in sedimentation and displacement, however occurs in the "Gully 1" transect of site O3, a distinctly convex watershed. In this transect, simulated average annual sediment delivery exceeds 17 Mg/ha, which potentially reflects a steeper percent slope at some points in the gully flow path. Meanwhile, a decreased sediment yield as BEINP value increases potentially indicates that increased litter and ground cover on highly productive prairie areas helps trap sediment as it flows down the hillslope.

Future Directions

The next steps for WEPP research in row-crop-prairie systems will be to fine tune the 100% row-crop predictions and to expand the simulations to STRIPS2 sites. Site-specific crop and management data such as farmers would have access to on their own fields, and/or the incorporation of STRIPS agronomic data, would enable the model to more accurately represent crop yield, biomass, and residue. Management would also help ensure that management is modeled with consideration of weather patterns, as farmers would do in a real-life situation. Although the interface is relatively user-friendly, an updated interface with interactive tutorials, a more intuitive process for incorporating site-specific data, and shortcuts for adjusting key parameters could improve usability among farmers interested in conservation strategies or even in educational settings.

Soil erodibility and other soil and crop parameters were not adjusted in this study and in the future may be able to correct for the overestimation of sediment export. For example, WEPP is sensitive to soil erodibility parameters, especially rill erodibility (K_r). Parameterization of rill erodibility, and potentially other soil properties such as shear stress (τ_c), aggregate stability, soil detachability, and splash detachment, may be quite effective in improving predictions (Gumiere, 2009). Hydrological phenomena that influence runoff capability are also driving factors for predicting erosion. For instance, interrill erosion is sensitive to the square of rainfall intensity (Gumiere, 2009) and to saturated hydraulic conductivity (Nearing, et al., 1990). While conducting testing onsite can provide empirical values for these factors, using a modified equation based on a STRIPS calibration dataset and adjusting until results match is also possible (Laflen et al., 1991; Robichaud, 1996; Flanagan et al., 2012) and may be a more feasible option for farmers and consultants. As STRIPS2 sites continue to be monitored, WEPP simulations can be compared with data from a number of sites with diverse soils, climates, and topography.

To obtain a more accurate long-term prediction, it may be necessary to run a longer-term simulation on real precipitation data to more effectively balance out extreme years. Alternatively, as recent years have been warmer and drier, an alternative strategy may be to substitute climate data from a nearby area with lower annual precipitation to provide a longer-term approximation of these recent conditions.

A potential source of discrepancy between predictions and observations is erosion and precipitation during the “freezing season,” when runoff and sediment were not measured. An important question for future work is whether WEPP appropriately captures erosion during the winter “freezing season,” and how this may or may not have escaped the H-flume recordings. For instance, the H-flume data collected during the non-freezing season (referred to as the growing season) may not capture the soil and water movement that comes from repeated freezing, precipitation, and thawing of the land several times at the beginning or end of winter. In addition, this study did not seed the model with any existing snow on the ground on Julian Day 1. Informative future studies would also include investigating how to properly seed the model with an appropriate amount of snow present at the beginning of Julian Year 1, which was not conducted in this study.

Experimenting with ways to simulate different prairie compositions could also be a next step. For example, adjusting land cover parameters in the initial year has the potential to more realistically model young strips that are just becoming established.

Future work that breaks down results by year could help determine which years overestimate and underestimate sediment yield. In addition, it would enable researchers to isolate the initial year while strips are being established from the analysis to determine if it is representative of the behavior of older prairies. Although the WEPP hillslope model does not have the capacity to output monthly averages, data could be exported to the WEPP watershed model and monitored at a simulated impoundment, which can return monthly averages and annual averages.

The watershed model includes gully erosion modeling and can support many simulated hillslopes joining together in waterways and flowpaths. A more involved, but potentially more accurate, project than simply importing a single hillslope per field into the watershed model would be to construct and calibrate a network of hillslopes for each field. Although this would potentially lead to more difficulty in calibration stages, it may lead to better predictions overall.

WEPP's sensitivity to prairie strip placement and design would be a further question to consider. If WEPP could provide accurate predictions with this level of detail, it would greatly help farmers design their prairie strip siting. For instance, soil loss profile graphs from the simulations seem to indicate that much of the sediment deposition occurs in the first few meters of a prairie area. Depending on the slope, climate, and other conditions, the results of the simulations could help them maximize the impact of their strips and determine the amount of prairie that will help them achieve their goals.

Finally, modeling enables the concept of 10% prairie integration to be explored on a larger scale before committing physical land to the project. For instance, a land manager may explore the influence of converting an entire sub-watershed to prairie on local attainment of nutrient reduction goals.

A tool commonly used in geospatial WEPP simulations is GeoWEPP, an interface designed to integrate WEPP with ArcGIS map software (3.0 or earlier). It simulates erosion on one or more watersheds in real space, either using default parameters or incorporating customized geographical data. In GeoWEPP, the user selects an area for simulation, and the program divides the area into subwatersheds, which in turn are subdivided into hillslopes that are modeled with WEPP. GeoWEPP simplifies land cover in its calculations and can only accommodate one land use per subwatershed. Because prairie strip integration occurs on a fine scale within subwatersheds themselves, GeoWEPP was rejected for the purposes of this study in favor of the standalone WEPP interface. However, for large-scale questions such as these, GeoWEPP may be a fruitful avenue of investigation.

Conclusion

The results from the mesh pad experiment and from the WEPP simulations confirm that prairie strips ameliorate soil and water loss on farmers' fields. Furthermore, WEPP holds potential as a tool to help predict and understand the potential benefits of new prairie installations.

WEPP simulations show that sediment export responds dramatically to native perennial integration. A sediment yield reduction of 97% is estimated on simulations with prairie strips, in close alignment with the 96% reduction indicated by H-flume data. Runoff variability was wide, but WEPP simulations indicate a significant runoff reduction of 27% on sites with prairie strips, and H-flume data suggest a runoff reduction of 45%, although this is not significant. The analysis of in-field displacement data indicates that integrating small amounts of prairie can also significantly reduce soil displacement in annual corn and soybean fields. On fields that include prairie strips, in-field erosion in the crop areas is reduced by over 30%.

All told, the results from the mesh pad experiment and the WEPP simulations provide continued evidence of the potential of prairie strip technology to move Iowa toward its water quality goals and to keep valuable soil on farmers' fields. WEPP holds promise as a way for farmers and their consultants to estimate the benefits that prairie strip technology could provide to their land. Continued study will enhance the capacity to predict and understand the potential benefits of new prairie strip installations.

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Appendices

Appendix A: Choice of Slope Resolution

Initial fitting of slope profile data involved approximating the slope at each point in the ArcGIS output slope profiles, then thinning out the points at regular intervals such that there were no more than 50 data points for each resulting WEPP-compatible slope file. This number was chosen as fifty is the highest number of slope data points supported by WEPP. The data points in the WEPP slope files resulting from this method were at times less than 2 m apart. As seen in the B3 watershed simulation, although these higher-resolution slope files did not appear to show any anomalies in the Slope Profile Editor panel (Figure 11) model runs behaved as though extreme spikes existed in the hillslope, leading in this case to a maximum detachment of 25.5 kg/m^2 at a distance of 56.1 m from the hilltop (Figure 12).

B3 High-Resolution Slope File

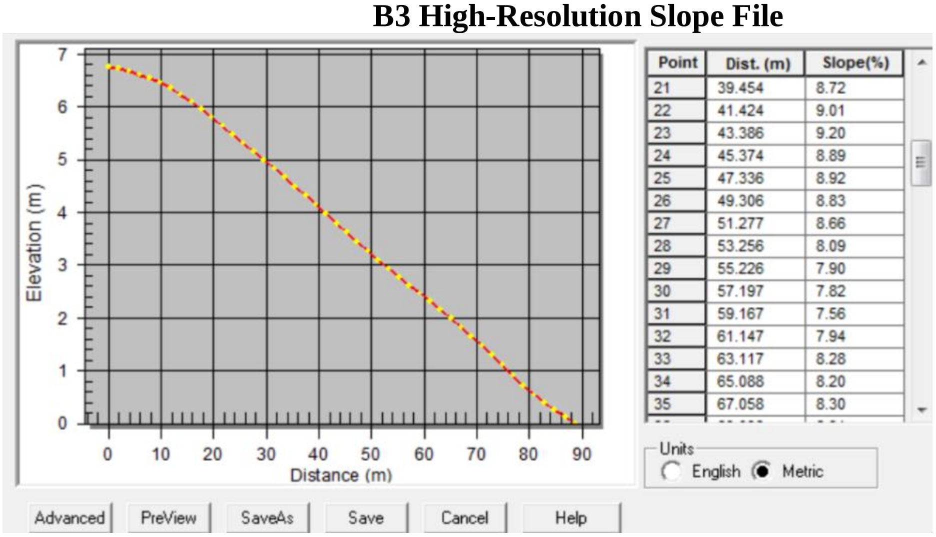

Figure 11: High-Resolution Slope Profile for B3 Watershed. The slope appears smooth.

As a result, the methodology was revised such that the limiting factor was not the number of data points in the slope, but rather the distance between each point. The new method involved taking the slope of each section of no less than 5m, then removing all other data points. The first and last data points were always included to maintain the accuracy of the slope length. In both cases, the "Curve" option, found under advanced settings in the slope editor interface, was used to smooth the profile.

Elevation and Rate of Erosion on B3 Using High-Resolution Slope File

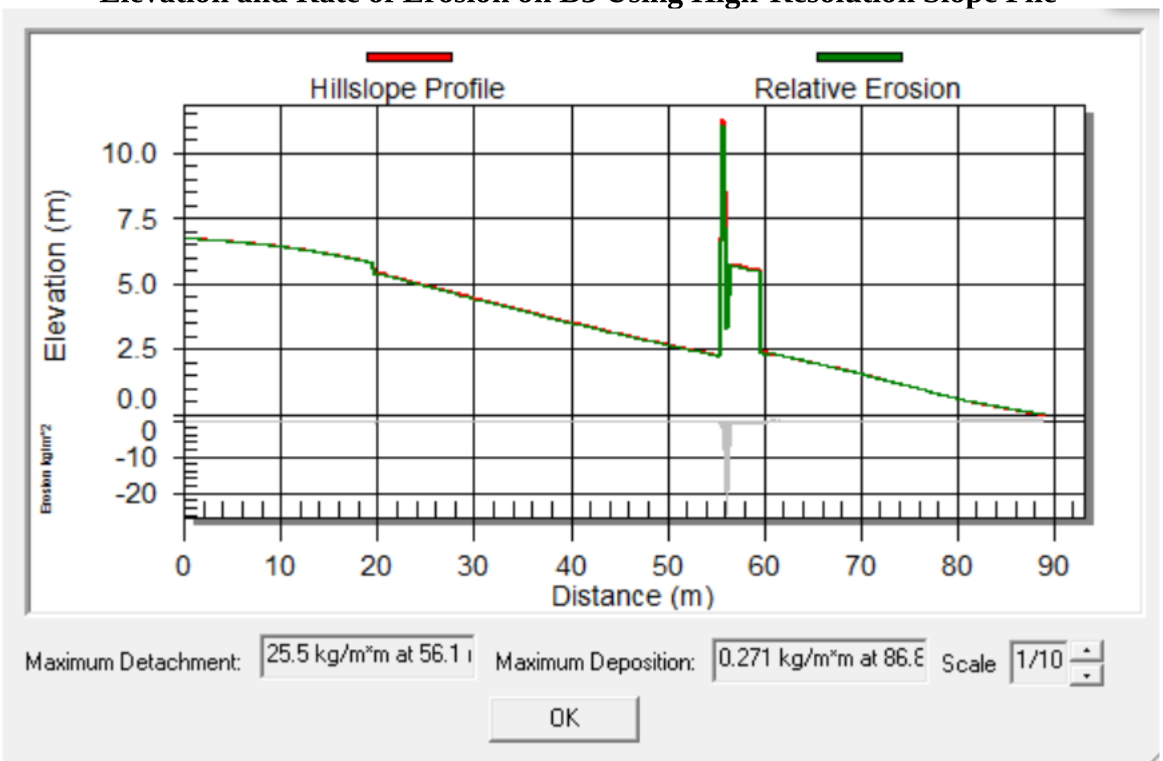

Figure 12: Soil Loss Graph for B3 Using High-Resolution Slope File. The model is behaving as though a spike in the hillslope at 56m is causing rampant erosion.

This adjustment eliminated anomalies in the slope profiles and resulting erosion patterns on the hillslopes. As a result, average soil displacement and sediment delivery results were also decreased. In watershed B3, for example, proper parametrization decreased average displacement from 0.47 kg/m^2 to 0.35 kg/m^2, and reduced sediment delivery from 0.55 Mg/ha to 0.37 Mg/ha.

Appendix B: Choice of Land Cover Type

A summary of a rough series of simulations for the years 2007-2010 on the I1 slope alone, with default prairie plant database files, is included in Table 14 below.

Table 14: Rough Prairie Plant Choice Simulations on Watershed I1 (2007-2010)

	Runoff (mm)	Soil Displacement (kg/m^2)	Sediment Yield (Mg/ha)
FairKS	143.8	1.11	6.03
FairNE	143.8	1.11	6.02
GoodKS	143.9	1.06	6.04
PoorKS	144.5	1.05	6.15
PoorNE	144.5	1.05	6.14

Appendix C: Corn-Soybean Rotation Phase

All watersheds were managed in a corn-soybean rotation, beginning with soybeans in 2007. A sample comparison of a simulation with a properly phased rotation beginning with soybean in the year 2007, alongside an improperly phased rotation beginning with corn in the year 2007, is included below for the watershed B4 in Table 15.

Table 15: Impact of Crop Rotation Phase on WEPP Outputs for B4 (2007-2014)

	Runoff (mm)	Soil Displacement (kg/m^2)	Sediment Yield (Mg/ha)
Proper Crop Rotation	87.3	0.63	0.37
Improper Crop Rotation	88.8	0.30	0.72

Appendix D: Plant Calibration

The reasoning behind the adjustments in base daily air temperature and Darcy–Weisbach maximum friction factor is described in the Methods section. The adjustment to plant spacing shown below is an upper bound on the density of the prairie, since the average stem width is 0.22 cm while plant spacing is only slightly greater, at 0.25 cm. While in theory increased density can reduce the velocity of surface runoff as it traverses the prairie and by extension also reduce sediment delivery, adjustment to plant spacing had little impact on sediment delivery in the simulation below. For this reason, a more moderate plant spacing value of 0.5 cm was used in the final calibration.

The biomass energy ratio (BEINP) was calibrated such that the simulated peak live biomass on the prairie segments matched empirical data for prairie strip installations in Iowa. A 106-year simulation was conducted on I1 with CLIGEN-generated data from the nearest-available weather station (NEWTON IA). Calibrated values were used for the other plant parameters: 0.5 cm plant spacing, 4.4°F base daily air temperature, and Darcy–Weisbach maximum friction factor of 136. WEPP plant output was processed in Excel, to find average peak live biomass over the 100-year period from Julian Year 6 to Julian Year 105. Processing was conducted with a multi-level sort: by year, ascending, then by overland flow element, which delineate segments of the slope with unique soil type and management inputs, then by live biomass, descending. A filter was then applied on crop index to keep only the prairie segments (crop index 3, or Overland Flow Elements 3, 5, and 8). Next, Remove Duplicates in Data Tools was applied to only keep the first row for each Julian year and overland flow element. Finally, hidden columns were removed and the 100-year average live biomass was calculated for the prairie segments.

As indicated in Table 16, a BEINP of 16 gave a live biomass output of approximately 11,200 kg/ha on par with a conservative estimate of live biomass for established strips. A BEINP of 20 gave an output of approximately 14,400 kg/ha, comparable to the most productive established strips sites. A BEINP of 12 gave a live biomass output of approximately 7990 kg/ha, on par with that seen in first-year strips.

Table 16: Effect of BEINP on Average Annual Peak Live Prairie Biomass

BEINP Value	Average Annual Peak Live Prairie Biomass (kg/ha)
12	7990
16	11,200
20	14,400
25	18,500

A side-by-side comparison of the default settings to simulations with individual parameter adjustments is included below (Table 17).

Table 17: Sediment Delivery on I1, 2007-2010 With Various Plant Parameter Adjustments

Simulation Adjustment	Parameter Details	Sediment Delivery (Mg/ha)	Runoff (mm)	Displacement (kg/m^2)
Default Values for All Four Parameters	Base Daily Air Temperature = 10°F, Plant Spacing = 0.6 cm, FLIVMX = 12, BEINP = 25 kg/MJ	6.04	143.9	1.06
Base Daily Air Temperature	Decreased from 10°F to 4.4°F. (Others = default)	5.99	142.4	1.07
Plant Spacing	Decreased from 0.6 cm to 0.25 cm. (Others = default)	6.04	143.9	1.06
Darcy–Weisbach Maximum Friction Factor (FLIVMX)	Increased from 12 to 136. (Others = default)	0.59	141.5	0.94
Biomass Energy Ratio (BEINP)	Decreased from 25 kg/MJ to 16 kg/MJ. (Others = default)	6.18	144.5	1.05
Final Calibration	Base Daily Air Temperature = 4.4°F, Plant Spacing = 0.5 cm, FLIVMX = 136, BEINP = 16 kg/MJ	0.58	140.3	0.95

Appendix E: Empirical Annual Sediment Delivery and Runoff by Watershed

Table 18: Empirical Annual Sediment Delivery and Runoff by Watershed

Watershed	Year	Sediment Delivery in Mg/ha (Chris Witte and Matt Helmers, unpublished data)	Runoff in mm (GitHub, Chris Witte and Matt Helmers)
B1	2007	39.37	63.2
B1	2008	9.83	22.6
B1	2009	73.20	73.8
B1	2010	361.55	232.2
B1	2011	142.32	94.7
B1	2012	79.39	26.8
B1	2013	32.83	55.3
B1	2014	4.69	44.6
B2	2007	0.00	6.9
B2	2008	1289.34	323.7
B2	2009	154.54	154.1
B2	2010	386.08	476.4
B2	2011	199.91	111.7
B2	2012	5.03	5.8
B2	2013	8.50	42.1
B2	2014	8.59	57.4
B3	2007	89.49	35.4
B3	2008	107.40	77.7
B3	2009	18.52	48.3
B3	2010	416.68	309.4
B3	2011	136.11	74.9
B3	2012	0.57	12.6
B3	2013	56.62	85.8
B3	2014	6.95	102.3
B4	2007	211.35	77.3
B4	2008	2405.52	278.2
B4	2009	334.30	154.7
B4	2010	1352.82	569.7
B4	2011	181.37	177.9
B4	2012	106.68	21.4
B4	2013	315.73	110.1
B4	2014	59.78	162.3
B5	2007	111.07	81.3

B5	2008	656.85	143.5
B5	2009	0.00	99.3
B5	2010	158.65	334.4
B5	2011	118.94	134.9
B5	2012	71.12	14.0
B5	2013	13.20	50.2
B5	2014	23.26	69.2
B6	2007	139.66	80.2
B6	2008	24702.52	302.0
B6	2009	2730.95	187.0
B6	2010	14472.07	714.5
B6	2011	1242.21	262.8
B6	2012	1790.25	44.9
B6	2013	6951.00	233.6
B6	2014	603.43	141.9
I1	2007	4.32	9.7
I1	2008	1015.26	67.0
I1	2009	52.47	36.2
I1	2010	445.62	178.3
I1	2011	1142.19	95.2
I1	2012	7.58	4.6
I1	2013	148.94	52.3
I1	2014	1.98	53.4
I2	2007	9.38	10.1
I2	2008	1228.13	82.7
I2	2009	165.20	63.7
I2	2010	228.88	219.9
I2	2011	1143.28	89.7
I2	2012	51.85	6.3
I2	2013	44.76	54.5
I2	2014	1.46	34.8
I3	2007	25.59	32.2
I3	2008	38920.97	206.4
I3	2009	5764.36	148.0
I3	2010	7894.93	410.6
I3	2011	861.38	161.4
I3	2012	1626.99	41.5
I3	2013	2676.07	129.7
I3	2014	581.74	152.5

O1	2007	0.00	1.3
O1	2008	735.60	78.1
O1	2009	27.45	23.0
O1	2010	0.00	75.9
O1	2011	252.05	77.6
O1	2012	35.74	6.2
O1	2013	138.16	78.0
O1	2014	25.96	72.9
O2	2007	0.00	11.0
O2	2008	713.71	66.7
O2	2009	57.21	19.4
O2	2010	212.14	198.4
O2	2011	314.65	85.3
O2	2012	0.36	1.5
O2	2013	89.70	48.1
O2	2014	1.76	25.6
O3	2007	0.00	5.0
O3	2008	8156.10	71.1
O3	2009	347.17	52.0
O3	2010	5470.86	308.3
O3	2011	1868.97	101.8
O3	2012	117.88	4.0
O3	2013	1698.82	238.7
O3	2014	39.93	33.6

Appendix F: R Outputs: Linear Model Summary Statistics on Sediment and Runoff for Simulations and H-flume Data

Figure 13: Estimate of Treatment Effect with lmer1 and lm1 Model:

```
> lmer1_confint_exp
   estimate       SE     df t_ratio p_value  lower_CL  upper_CL
1 0.6741358 1.099317 164.55  -4.164   1e-04 0.5591793 0.8127252

> lm1_confint_exp
   estimate       SE  df t_ratio p_value  lower_CL  upper_CL
1 0.6741358 1.099239 165  -4.168 <0.0001 0.5592596 0.8126085
```

Figure 14: F Values and Estimate of Random Effects for the lmer1 Model:

```
> Anova(lmer1,type="III",test.statistic="F")
Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Response: ilog_soil_g_per_day
                    F Df Df.res    Pr(>F)    
(Intercept)    1.2298  1  14.13   0.28597    
treatment     17.3424  1 165.02 5.019e-05 ***
factor(year)  19.1180  2 153.69 3.849e-08 ***
survey         2.0004  2 166.81   0.13852    
position       2.9816  2 165.02   0.05345 .  
crop           3.1829  1 167.77   0.07622 .  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Random effects:
 Groups   Name        Variance Std.Dev.
 property (Intercept) 0.7846   0.8858  
 Residual             0.4035   0.6352  
Number of obs: 180, groups:  property, 7
```

Figure 15: Construction and Covariates of the lmer3 Model:

```
lmer3 <- lmer(ilog_soil_g_per_day ~treatment*position+
                     factor(year)+survey+
                     (1|property)+(1|property:treatment)+
                     (1|property:survey)+
                     (1|property:treatment:survey), data = summ)
```

Figure 16: Significance of Fixed and Random Effects in Exploratory Model:

```
> Anova(lmer3,type="III",test.statistic="F")
Analysis of Deviance Table (Type III Wald F tests with Kenward-Roger df)

Response: ilog_soil_g_per_day
                         F Df  Df.res    Pr(>F)    
(Intercept)         0.0465  1  20.864   0.83143    
treatment           6.8157  1  13.347   0.02119 *  
position            2.1879  2 137.149   0.11605    
factor(year)       36.0879  2 147.790 1.728e-13 ***
survey              0.4041  2  10.299   0.67773    
treatment:position  0.5945  2 137.149   0.55325    
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Random effects:
 Groups                    Name        Variance Std.Dev.
 property:treatment:survey (Intercept) 0.00000  0.0000  
 property:survey           (Intercept) 0.29082  0.5393  
 property:treatment        (Intercept) 0.05718  0.2391  
 property                  (Intercept) 0.63381  0.7961  
 Residual                              0.25051  0.5005  
```

Figure 17: Linear Model Results: Effect of Prairie Strip Treatment on Sediment Delivery in WEPP-Simulated Row-crop Systems:

```
Console ~/Documents/MillerThesisAnalysis/data-raw/
> lm_sediment_simulation <- lm(ilog_wepp_sediment_t_per_ha ~treatment_type, data = weppoutputs_c
lean)
> print(summary(lm_sediment_simulation))

Call:
lm(formula = ilog_wepp_sediment_t_per_ha ~ treatment_type, data = weppoutputs_clean)

Residuals:
     Min       1Q   Median       3Q      Max
-0.43779 -0.08424  0.03176  0.15065  0.31913

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)            2.4131     0.1304   18.50 4.59e-09 ***
treatment_typestrips  -3.5601     0.1506  -23.64 4.17e-10 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2259 on 10 degrees of freedom
Multiple R-squared:  0.9824,	Adjusted R-squared:  0.9807
F-statistic: 558.7 on 1 and 10 DF,  p-value: 4.169e-10

> print(exp(coef(lm_sediment_simulation)))
         (Intercept) treatment_typestrips
         11.16884348           0.02843652
> print(exp(confint(lm_sediment_simulation)))
                          2.5 %      97.5 %
(Intercept)          8.35187059 14.93594320
treatment_typestrips 0.02032942  0.03977663
> print(lsmeans_analysis_contrast <- lsmeans_analysis <-
+           lsmeans(lm_sediment_simulation, "treatment_type")%>%
+           contrast("trt.vs.ctrl"))
 contrast          estimate        SE df t.ratio p.value
 strips - control -3.560081 0.1506213 10 -23.636  <.0001

> print(exp(-3.560081))
[1] 0.02843652
```

Figure 18: Linear Model Results: Effect of Prairie Strip Treatment on Runoff in WEPP-Simulated Row-crop Systems:

```
> lm_runoff_simulation <- lm(ilog_wepp_runoff_mm ~treatment_type, data = weppoutputs_clean)
> print(summary(lm_runoff_simulation))

Call:
lm(formula = ilog_wepp_runoff_mm ~ treatment_type, data = weppoutputs_clean)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.36885 -0.04741  0.00358  0.09661  0.22625 

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)    
(Intercept)          4.81421    0.09745  49.404 2.79e-13 ***
treatment_typestrips -0.30892    0.11252  -2.745   0.0206 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.1688 on 10 degrees of freedom
Multiple R-squared:  0.4298,	Adjusted R-squared:  0.3728 
F-statistic: 7.537 on 1 and 10 DF,  p-value: 0.02064

> print(exp(coef(lm_runoff_simulation)))
         (Intercept) treatment_typestrips 
         123.2494496            0.7342418 
> print(exp(confint(lm_runoff_simulation)))
                          2.5 %      97.5 %
(Intercept)          99.1948618 153.1372346
treatment_typestrips  0.5714203   0.9434579
> print(lsmeans_analysis_contrast <- lsmeans_analysis <-
+           lsmeans(lm_runoff_simulation, "treatment_type")%>%
+           contrast("trt.vs.ctrl"))
 contrast          estimate        SE df t.ratio p.value
 strips - control -0.3089169 0.1125214 10  -2.745  0.0206

> print(exp(-.3089169))
[1] 0.7342418
```

Figure 19: Linear Model Results: Effect of Prairie Strip Treatment on Sediment Delivery Using H-Flume Data:

```
> lm_sediment_empirical <- lm(ilog_empirical_sediment_t_per_ha_from_witte ~treatment_type, data
= weppoutputs_clean)
> print(summary(lm_sediment_empirical))

Call:
lm(formula = ilog_empirical_sediment_t_per_ha_from_witte ~ treatment_type,
    data = weppoutputs_clean)

Residuals:
     Min       1Q   Median       3Q      Max
-0.80781 -0.45005  0.01288  0.45532  1.09193

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)           1.5550     0.3690   4.214  0.00179 **
treatment_typestrips  -3.1235    0.4261  -7.330 2.51e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6392 on 10 degrees of freedom
Multiple R-squared:  0.8431,    Adjusted R-squared:  0.8274
F-statistic: 53.73 on 1 and 10 DF,  p-value: 2.511e-05

> print(exp(coef(lm_sediment_empirical)))
         (Intercept) treatment_typestrips
          4.73515787           0.04400478
> print(exp(confint(lm_sediment_empirical)))
                          2.5 %     97.5 %
(Intercept)          2.08086855 10.7751737
treatment_typestrips 0.01702817  0.1137186
> print(lsmeans_analysis_contrast <- lsmeans_analysis <-
+           lsmeans(lm_sediment_empirical, "treatment_type")%>%
+           contrast("trt.vs.ctrl"))
 contrast          estimate        SE df t.ratio p.value
 strips - control -3.123457 0.4261086 10   -7.33  <.0001

> print(exp(-3.123457))
[1] 0.04400478
```

Figure 20: Linear Model Results: Effect of Prairie Strip Treatment on Runoff Using H-Flume Data:

```
> lm_runoff_empirical <- lm(ilog_empirical_runoff_mm_from_github ~treatment_type, data = weppout
puts_clean)
> print(summary(lm_runoff_empirical))

Call:
lm(formula = ilog_empirical_runoff_mm_from_github ~ treatment_type,
    data = weppoutputs_clean)

Residuals:
     Min       1Q   Median       3Q      Max
-0.52862 -0.36563 -0.06234  0.31868  0.79498

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)           5.0683     0.2596  19.522 2.72e-09 ***
treatment_typestrips -0.5957     0.2998  -1.987    0.075 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.4497 on 10 degrees of freedom
Multiple R-squared:  0.2831,    Adjusted R-squared:  0.2114
F-statistic: 3.948 on 1 and 10 DF,  p-value: 0.07499

> print(exp(coef(lm_runoff_empirical)))
         (Intercept) treatment_typestrips
         158.9072466            0.5511936
> print(exp(confint(lm_runoff_empirical)))
                          2.5 %     97.5 %
(Intercept)          89.1085829 283.379134
treatment_typestrips  0.2826282   1.074961
> print(lsmeans_analysis_contrast <- lsmeans_analysis <-
+            lsmeans(lm_runoff_empirical, "treatment_type")%>%
+            contrast("trt.vs.ctrl"))
 contrast           estimate         SE df t.ratio p.value
 strips - control -0.5956691 0.2997811 10  -1.987  0.0750

> print(exp(-.5956691))
[1] 0.5511936
```