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Native prairie filter strips reduce runoff from hillslopes under annual row-crop systems in Iowa, USA

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Abstract

Intensively managed annual cropping systems have produced high crop yields but have often produced significant ecosystem services alteration, in particular hydrologic regulation loss. Reconversion of annual agricultural systems to perennial vegetation can lead to hydrologic function restoration, but its effect is still not well understood. Therefore, our objective was to assess the effects of strategic introduction of different amounts and location of native prairie vegetation (NPV) within agricultural landscapes on hydrological regulation. The study was conducted in Iowa (USA), and consisted of a fully balanced, replicated, incomplete block design whereby 12 zero-order ephemeral flow watersheds received four treatments consisting of varying proportions (0%, 10%, and 20%) of prairie vegetation located in different watershed positions (footslope vs. contour strips). Runoff volume and rate were measured from 2008 to 2010 (April–October) with an H-Flume installed in each catchment, and automated ISCO samplers.

Over the entire study period, we observed a total of 129 runoff events with an average runoff volume reduction of 37% based on the three treatments with NPV compared to watersheds with row crops. We observed a progressively greater reduction across the 3 years of the study as the perennial strips became established with the greatest differences among treatments occurring in 2010. The differences among the watersheds were attributed mainly to NPV amount and position, with the 10% NPV at footslope treatment having the greatest runoff reduction probably because the portion of NPV filter strip that actually contacted watershed runoff was greater with the 10% NPV at footslope. We observed greater reductions in runoff in spring and fall likely because perennial prairie plants were active and crops were absent or not fully established. High antecedent soil moisture sometimes led to little benefit of the NPV treatments but in general the NPV treatments were effective during both small and large events. We conclude that, small amounts of NPV strategically incorporated into corn-soybean watersheds in the Midwest US can be used to effectively reduce runoff.

Keywords

Natural Resource Ecology and Management, Agricultural watersheds, Conservation practices, Corn belt, Hydrologic services restoration, Vegetative buffers, Width-position strips

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Natural Resources Management and Policy | Water Resource Management

Comments

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Native prairie filter strips reduce runoff from hillslopes under annual row-crop systems in Iowa, USA

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SUMMARY

Intensively managed annual cropping systems have produced high crop yields but have often produced significant ecosystem services alteration, in particular hydrologic regulation loss. Reconversion of annual agricultural systems to perennial vegetation can lead to hydrologic function restoration, but its effect is still not well understood. Therefore, our objective was to assess the effects of strategic introduction of different amounts and location of native prairie vegetation (NPV) within agricultural landscapes on hydrological regulation. The study was conducted in Iowa (USA), and consisted of a fully balanced, replicated, incomplete block design whereby 12 zero-order ephemeral flow watersheds received four treatments consisting of varying proportions (0%, 10%, and 20%) of prairie vegetation located in different watershed positions (footslope vs. contour strips). Runoff volume and rate were measured from 2008 to 2010 (April–October) with an H-Flume installed in each catchment, and automated ISCO samplers.

Over the entire study period, we observed a total of 129 runoff events with an average runoff volume reduction of 37% based on the three treatments with NPV compared to watersheds with row crops. We observed a progressively greater reduction across the 3 years of the study as the perennial strips became established with the greatest differences among treatments occurring in 2010. The differences among the watersheds were attributed mainly to NPV amount and position, with the 10% NPV at footslope treatment having the greatest runoff reduction probably because the portion of NPV filter strip that actually contacted watershed runoff was greater with the 10% NPV at footslope. We observed greater reductions in runoff in spring and fall likely because perennial prairie plants were active and crops were absent or not fully established. High antecedent soil moisture sometimes led to little benefit of the NPV treatments but in general the NPV treatments were effective during both small and large events. We conclude that, small amounts of NPV strategically incorporated into corn-soybean watersheds in the Midwest US can be used to effectively reduce runoff.

1. Introduction

The conversion of native vegetation to agricultural production systems to yield diverse goods and services represents one of the most substantial human alterations of the Earth system. The impact of this conversion is well recognized within the scientific community and it interacts strongly with most other components of global environmental change (Ramankutty and Foley, 1999; Vitousek et al., 1997). Agriculture affects ecosystems through the use and release of limited resources that influence ecosystem function (e.g. nitrogen, phosphorus, and water), release of pesticides, and biodiversity loss (Tilman et al., 2001), all of which can alter the availability of diverse ecosystem services (MEA, 2005). In particular, agriculture has been one of the major drivers of increasing water scarcity, declining water quality, and loss of flood regulation capacity worldwide (Houet et al., 2010). Agricultural production, and its related hydrological changes, have greatly increased during the 20th century and are expected to continue in the 21st century (Gordon et al., 2008). These impacts of agriculture on diverse hydrologic services represent a major threat to the well-being of human populations in many regions across the globe (MEA, 2005).

The Corn Belt of the Midwestern US has experienced one of the most dramatic and complete landscape scale conversions from na-

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tive perennial ecosystems to monoculture annual cropping systems. In this region, approximately 70% of the pre-European settlement prairies, savannas, riparian forests, and wetlands have been converted to annual crops (NASS, 2004), and the region now produces approximately 40% of the world's total annual corn yield (USDA, 2005). However, the environmental consequences of these changes are increasingly becoming apparent, including documented increases in baseflow (Schilling and Libra, 2003; Zhang and Schilling, 2006), contamination of water supplies (Jaynes et al., 1999; Goolsby and Battaglin, 2001), diminished flood control (Knox, 1999), all of which have far-reaching social and economic consequences (Alexander et al., 2009; Schilling et al., 2008; Rabalais et al., 2010).

In contrast to annual cropping systems, perennial vegetation can have positive impacts on hydrologic regulation (defined as the combined effect of increased evapotranspiration, infiltration and interception of runoff). Perennial vegetation has greater rainfall interception (Bosch and Hewlett, 1982; Brye et al., 2000), greater water use (Brye et al., 2000; Livesley et al., 2004; Anderson et al., 2009), deeper and more extensive rooting system (Jackson et al., 1996; Asbjornsen et al., 2007, 2008), extended phenology (Asbjornsen et al., 2008), and greater diversity in species and functional groups, conferring advantages for productivity and resilience (Tilman et al., 2001). Moreover, perennial vegetation can improve soil structure and hydraulic properties by increasing the number and size of macropores (Yunusa et al., 2002; Seobi et al., 2005) and building organic matter (Liebig et al., 2005; Tufekcioglu et al., 2003), which combined contribute to increasing soil water infiltration and hydraulic conductivity (Bharati et al., 2002; Udawatta et al., 2006, 2008).

Reversing the process of agricultural expansion and intensification by restoring native prairie vegetation is not realistic given the goal to meet important societal needs for global food, fuel, and fiber (Tilman et al., 2001). Moreover, technology, knowledge and policy frameworks for effectively managing large-scale highly diverse perennial-based production systems are not yet available (Glover et al., 2007). A promising alternative approach involves the incorporation of relatively small amounts of perennial cover in strategic locations within agricultural landscapes (Asbjornsen et al. in review). Over the past decade, policies have targeted such conservation practices by, for example, promoting the establishment of riparian buffer systems, and grass waterways (Feng et al., 2004). However, achieving the most appropriate balance for maximizing hydrologic functions proportional to the amount of land removed from production will require a better understanding on the influence of spatial extent, position, and type of perennial vegetation within a watershed (Dosskey et al., 2002; Blanco-Canqui et al., 2006), about which little empirical field data exist.

Presently, the most reliable field-based information available on effects of perennial cover on agricultural watershed hydrology comes from research on riparian and grass buffer systems with various studies reviewing their effects (Castelle et al., 1994; Liu et al., 2008; Zhang et al., 2010). While the buffer literature is extensive, little research has been done assessing perennial vegetation higher up in the landscape. A few field and plot level studies (Udawatta et al., 2002; Blanco-Canqui et al., 2006; Jiang et al., 2007) as well as modeling efforts (Geza et al., 2009) have begun to address the strategic placement of perennial vegetation, but most works are plot studies with controlled flow paths. Thus, there is a need to better understand the in-field performance of vegetative filters where flow is not controlled in some manner (Baker et al., 2006). The effectiveness of vegetative filters will vary significantly, depending upon the area of the filter that overland flow will encounter and the flow conditions in a filter, e.g. concentration of flow (Helmers et al., 2008).

Research is needed to determine how the amount and placement of perennial vegetation within agricultural watersheds can affect hydrological regulation. This would help determine the proper design of conservation practices that strategically places perennial vegetation in the landscape. In this study we incorporated perennial vegetation filter strips that varied by the area and location in the uplands of 12 zero-order watersheds that typically only flowed following snowmelt or following sizable rain events (ephemeral systems). The objective of our study was to assess the effects of strategic placement of native prairie vegetation (NPV) that varied by the landscape position and % of overall watershed cover on: (1) total runoff export from the experimental watersheds, and (2) the effects of annual and seasonal variation in rainfall on watershed response. Additionally, we sought to (3) determine the optimal size and location of native prairie vegetation for achieving maximum hydrologic benefits. Our central hypothesis was that strategic incorporation of small amounts of NPV into annual cropping systems would result in runoff reduction due to the greater hydrological regulation using NPV compared to annual crops. We further expected that differences between treatments would be greater during periods when annual crops were less active (e.g., early spring, late summer) and for smaller rainfall events, where the regulation capacity of NPV strips compared to the annual crops would likely be maximized.

2. Study design and methods

2.1. Site description

The study was conducted at the Neal Smith National Wildlife Refuge (NSNWR, 41°33′N, 93°16′W), a 3000 ha area managed by the U.S. National Fish and Wildlife Service, located in the Walnut Creek watershed in Jasper County, Iowa (Fig. 1). The NSNWR comprises part of the southern Iowa drift plain (Major Land Resource Area 108C) (USDA Natural Resources Conservation Service, 2006), which consists of steep rolling hills of Wisconsin-age loess on pre-Illinoian till (Prior, 1991). The landscape is well dissected by streams and ephemeral drainage ways. Most soils at the research sites are classified as Ladoga (Mollic Hapludalf) or Otley (Oxyaquic Argiudolls) soil series with 5–14% slopes and are highly erodible (Nestrud and Worster, 1979). The mean annual precipitation over the last 30 year is 850 mm, with most large storms occurring between May and July, measured at the National Ocean and Atmospheric Administration station at the NSNWR.

2.2. Experimental design

The study was implemented using a balanced incomplete block design with 12 small, zero-order watersheds distributed across four blocks. Zero-order watersheds refer to naturally- formed topographic hollows on hillslopes that concentrate and convey surface runoff water downslope following rainfall events. These zero-order watersheds have no perennial discharge and only exhibit ephemeral discharge in their hydrologic flow regime (American Rivers, 2007). Two blocks were located at Basswood (six watersheds), one block at Interim (three watersheds), and one block at Orbweaver (three watersheds) sites (Fig. 1). The size of these ephemeral watersheds varied from 0.5 to 3.2 ha, with average slopes ranging from 6.1% to 10.5% (Table 1). Each watershed received one of four treatments (three replicates per treatment): 100% rowcrop (100RC, control condition), 10% NPV in a single filter strip at the footslope position (10FootNPV), 10% NPV distributed among multiple contour filter strips at footslope and backslope positions (10StNPV), and 20% NPV distributed at the footslope position and in contour strips further up in the watershed (20StNPV) (Table 1). These

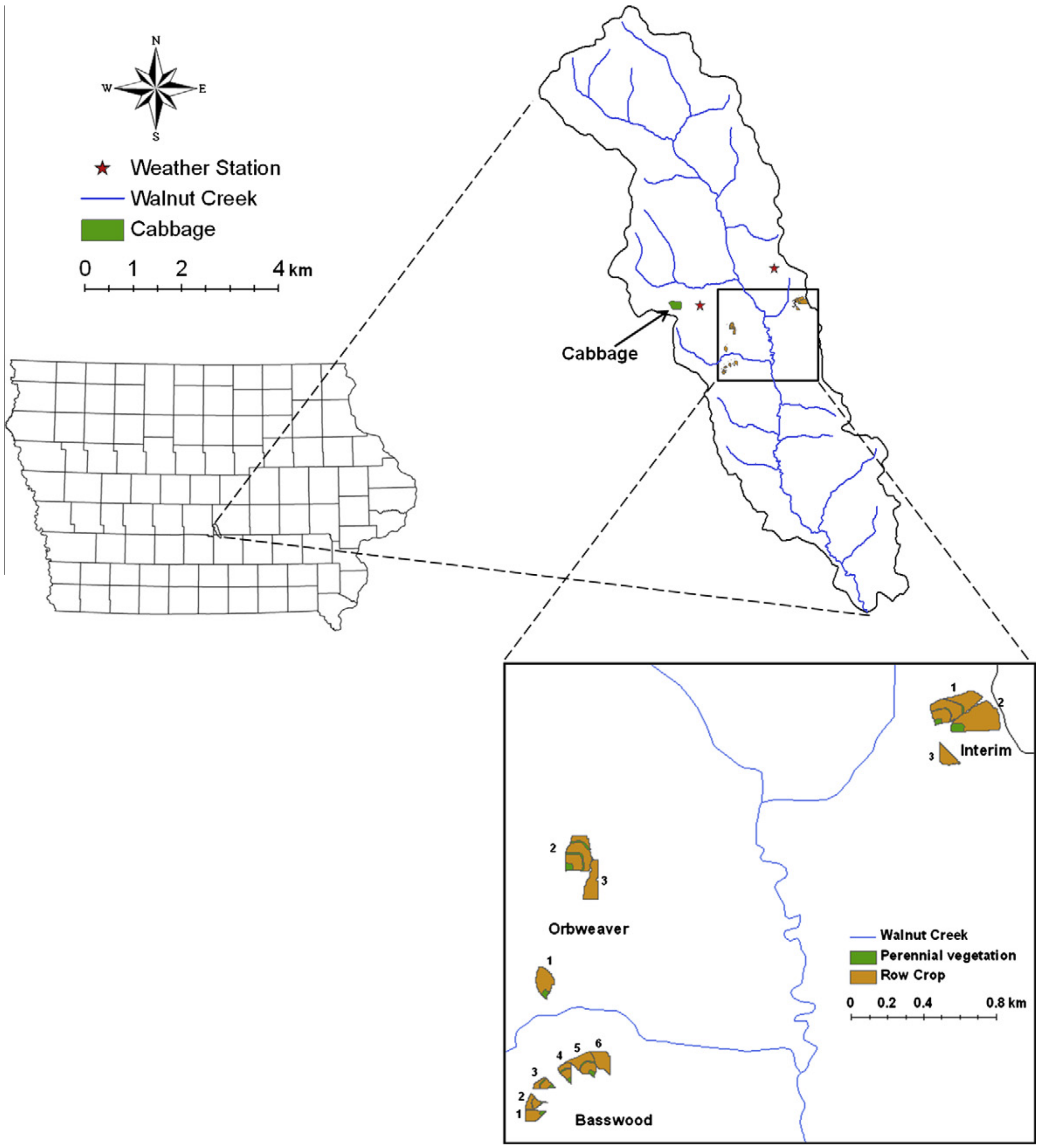

Fig. 1. Location of Walnut Creek watershed in Iowa (USA) and experimental design of vegetative filters for the study watersheds at Basswood, Interim, and Orbweaver.

Table 1
General watershed characteristics and description of treatments imposed on the experimental watersheds.

	Size (ha)	Slope (%)	Location and percentage of grass filters[a]	Number of strips
Basswood-1	0.53	7.5	10% at footslope	1 at footslope
Basswood-2	0.48	6.6	5% at footslope and 5% at shoulder	2, 1 at footslope and 1 at shoulder
Basswood-3	0.47	6.4	10% at footslope and 10% shoulder	2, 1 at footslope and 1 at shoulder
Basswood-4	0.55	8.2	10% at footslope and 10% shoulder	2, 1 at footslope and 1 at shoulder
Basswood-5	1.24	8.9	5% at footslope and 5% shoulder	2, 1 at footslope and 1 at shoulder
Basswood-6	0.84	10.5	All rowcrops	0
Interim-1	3.00	7.7	3.3% at footslope, 3.3% at backslope, and 3.3% at shoulder	3, 1 at footslope, 1 at backslope, and 1 at shoulder
Interim-2	3.19	6.1	10% at footslope	1 at footslope
Interim-3	0.73	9.3	All rowcrops	0
Orbweaver-1	1.18	10.3	10% at footslope	1 at footslope
Orbweaver-2	2.40	6.7	6.7% at footslope, 6.7% at backslope, and 6.7% at shoulder	3, 1 at footslope, 1 at backslope and 1 at shoulder
Orbweaver-3	1.24	6.6	All rowcrops	0

[a] Percentage of grass filters = area of filters/area of watershed.

proportions were selected based on model simulations suggesting that rapid increases in sediment trapping efficiency of buffers should occur within the 0–20% perennial cover range (Dosskey et al., 2002). One treatment was randomly withheld from each block, and the remaining three treatments assigned to each block were randomly placed among the block's three ephemeral watersheds. The width of NPV varied from 27 to 41 m at footslope, and 5–10 m at shoulder and backslope positions. Two additional watersheds (4.2 and 5.1 ha) also within NSNWR and having 100% reconstructed native prairie (100NPV) were also included in the study to provide a prairie reference (Schilling et al., 2007; Tomer et al., 2010). The two reference watersheds in Site 0 (Fig. 1) are not part of the balanced incomplete block experimental design but because of their proximity to our treatment watersheds we use them as reference watersheds for comparisons during 2009 and 2010 when the flumes were operational.

Prior to treatment implementation, all four experimental blocks were in bromegrass (*Bromus* L.) for at least 10 years. Pretreatment data were collected in 2005 and the first half of 2006. In August 2006, all watersheds were uniformly tilled with a mulch tiller. Starting in spring 2007, a 2-year no-till corn–soybean rotation (soybean in 2007) was implemented in areas receiving the rowcrop treatment. Weed and nutrient management practices were uniformly applied among the watersheds. Areas receiving NPV treatment were seeded with a diverse mixture of native prairie forbs and grasses using a broadcast seeder on 7 July 2007. The seed mix contained > 20 species in total, with the four primary species consisting of indiangrass (*Sorghastrum* Nash), little bluestem (*Schizachyrium* Nees), big bluestem (*Andropogon gerardii* Vitman), and aster (*Aster* L.). This method of seeding is consistent with methods used for other prairie reconstructions at the NSNWR. No fertilizer was applied in the NPV areas.

2.3. Rainfall

Hourly precipitation was obtained from the nearby Mesowest weather station operated by the National Weather Service, which is about 1.3–3.6 km from the study watersheds and fairly centrally located between sites. In addition, in each block rainfall was measured with a rain gauge that collected data every 5 min (ISCO 674, Teledyne Isco, Inc., NE, USA) which allowed us to measure time to runoff initiation and peak. For the other rainfall calculations (amount and intensity) the data from the Mesowest weather station were used since they allow historical rainfall comparisons.

2.4. Surface runoff

A fiberglass H flume was installed at the bottom of each watershed in 2005 and early 2006 according to the field manual for research in agricultural hydrology (Brakensiek et al., 1979). The flume size was determined based on the runoff volume and peak flow rate for a 10-year, 24-h storm. Runoff volume was estimated using the Soil Conservation Service Curve Number (SCS-CN) method using the curve number for cultivated land with conservation treatment (Hann et al., 1994). A total of eight 2-ft H-flumes and four 2.5-ft H-flumes were installed. Plywood wing walls were inserted at the bottom of watershed to guide surface runoff to the flumes. ISCO 6712 automated water samplers (ISCO, Inc., Lincoln, NE) equipped with pressure transducers (720 Submerged Probe Module) were installed at each flume to record runoff rate and collect water samples from April through October since 2007. ISCO units were removed from the field during winter (November–March) to avoid possible damage from freezing conditions. Flumes were checked to be level in spring of each year when the ISCO units were put back in the field. Flumes were also cleaned whenever sediment became deposited in them during runoff events. Flow stage was continuously measured by a pressure transducer and logged every 5 min. Pressure transducers were also calibrated in the laboratory every year when they were removed from the field and were regularly checked during the monitoring period. For each flume flow discharge rate was determined using the stage-discharge rating curve for that specific flume (Walkowiak, 2006). The volume of flow within every 5 min was then calculated and summed to obtain the total flow volume for each event. In 2006, there were no rainfall events that produced surface runoff through the flumes. In 2007, runoff varied from 5 to 86 mm, but no treatment effects were evident in the first year of post-treatment data. Thus, we present data from 2008, 2009, and 2010, from April to October. In 2010, one of the watersheds was not used in the analysis (Weaver1, 10FootNPV) due to equipment malfunction. We observed some small but continuous flow at some watersheds, especially Basswood2. However, considering the small size of the watersheds, significant base flow is not probable and was likely due to a seep. Continuous flow data were not included in the analysis, only event based flow.

2.5. Statistical analyses

To test for significant differences in surface runoff between experimental treatments (%NPV and position vs. cropland) for 2008–2010 we used the PROC MIXED procedure (a generalization of General Linear Model GLM procedure) of SAS (SAS Institute, 2001). The same analysis was used to test for significant differences among the reference watersheds (100NPV), the experimental treatments with different%NPV and 100RC for 2009 and 2010. The variables analyzed were runoff volume, average runoff rate, peak flow, runoff coefficient, time to first peak and time to start of runoff. The runoff coefficient is defined as the ratio of runoff to precipitation. Because of the similarity in landscape, soil formation, and management history among the watersheds, watersheds receiving the same treatment were regarded as randomized replicates (no block effect included). The runoff data were transformed for the analysis (square root transformation) to fix non-constant variance in residuals. We also used the MODEL statement of SAS including the interaction term (RAINFALL $*$ RUNOFF) to test whether the slopes of the regression lines for rainfall-runoff volume were significantly different.

We chose $\alpha = 0.1$ and report all p values < 0.1, allowing the reader to compare statistical results against an alternate α value (e.g., 0.05). Given the incomplete blocking, natural landscape variability among test watersheds, and inherent measurement error involved in hydrologic measurements using flumes, $\alpha = 0.1$ is an appropriate indicator of statistical significance for this experiment. However, we distinguish results with p values < 0.1 as 'significant', and report results with p values < 0.05 as 'highly significant'. To gain a better understanding of the hydrologic function of the NPV strips, runoff events were grouped as large events (>10 mm runoff, averaged among all plots) or small events (<2 mm runoff) based on their volume, with moderate runoff events between 2 and 10 mm runoff. While arbitrary, the 10 mm threshold includes events with an average return interval of about 1 year (the 2-year runoff event was estimated to be 25 mm runoff). The 2 mm threshold for small events reflected small and relatively frequent events and included about 60% of the events observed during 2008–2010. The other hydrological variables analyzed were also classified based on this criterion. Additionally, events were further classified based on crop phenology: crops dormant season events or very early growing season (April to mid-June and mid-September to October) and crops active growing season events (from mid-June to mid-September). Only in crops active growing season events were crops considered to be fully mature and actively using substantial amounts of water. The same statistical analyses described above were used to determine differences among the treatments in these groups.

3. Results

3.1. Rainfall

A total of 149 rainfall events were analyzed during the study period, where a rainfall event was defined as rainfall that occurs after a rainless interval of at least 12 h duration. According to our experience this inter-event time is a good compromise between the independence of widely-spaced events and their increasingly variable intra-event characteristics (Dunkerley, 2008). Surface runoff occurred in at least one watershed for 129 of the rainfall events.

Precipitation in the NSNWR was highly variable during the study period (Fig. 2), ranging from 824 mm in 2009, 982 mm in 2008 and 1247 mm in 2010. The highest intensity rain in any 60 min period (mm h^{-1}) in a year was also greater for 2010 (40.4 mm h^{-1}) although similar to 2008 (40.1 mm h^{-1}), and lowest for 2009 (15.5 mm h^{-1}). Regarding seasonal variation (Table 2), the highest amount, intensity and number of rainfall events were registered in summer, whereas the lowest values occurred in fall. Some of the greatest intensity events during the study period (2008–2010) were registered in 2010 within a time period of 24 d starting July 18th. Four events out of 10 registered in these 24 d were the highest intensity of the study period (2008–2010), above 28.4 mm h^{-1} in all cases. In this period 430 mm was recorded, which is 29% of the total amount observed in 2010.

3.2. Hydrological response to rainfall and NPV effect

The slopes of the regression equations rainfall-runoff volume (mm) that can be used as a parameter to interpret the effect of the different NPV treatments are shown in Fig. 3 (R^2 = 0.53–0.60, p < 0.0001 in all cases). The slope was higher for 100RC and lower for 10FootNPV, with intermediate values for the other two watershed treatments with NPV distributed in strips. The differences among the slopes were highly significant (p = 0.008). The watersheds were responsive (i.e. the smallest rainfall event that generated runoff from all 12 watersheds) to rainfall values above 3.4 mm. For all treatments most of the cumulative total runoff volume occurred from events that were < 50 mm (Fig. 4).

Mean cumulative runoff for the 12 watersheds showed high variability across years (2008: 152 mm; 2009: 80 mm; 2010:

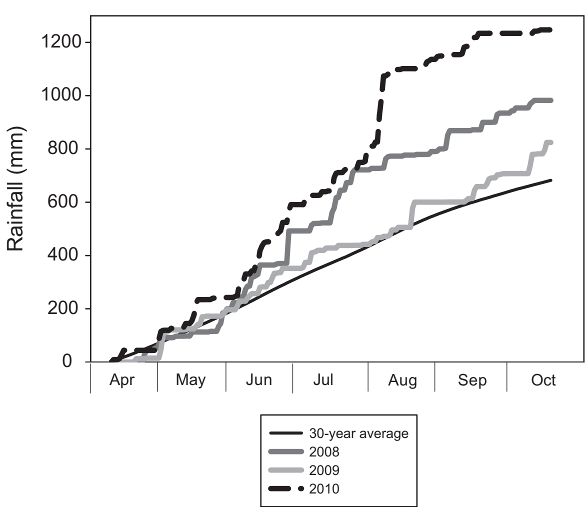

Fig. 2. Cumulative rainfall during the study period (April–October 2008–2010) and 30-year average.

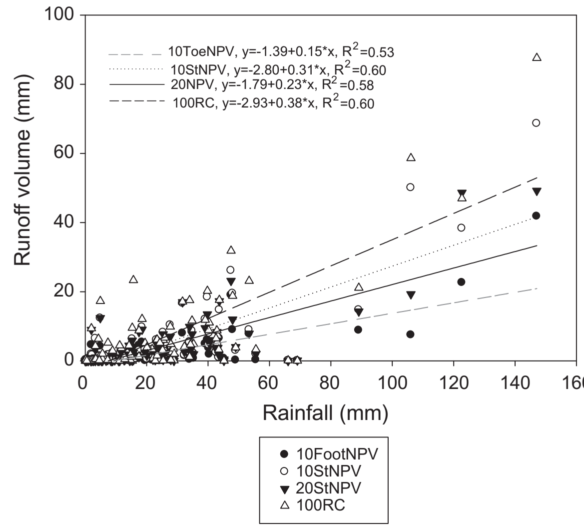

Fig. 3. Relationship between rainfall (mm) and runoff volume (mm) for each treatment. Each point represents the event average of the three watersheds for each treatment (10FootNPV, 10StNPV, 20StNPV and 100RC).

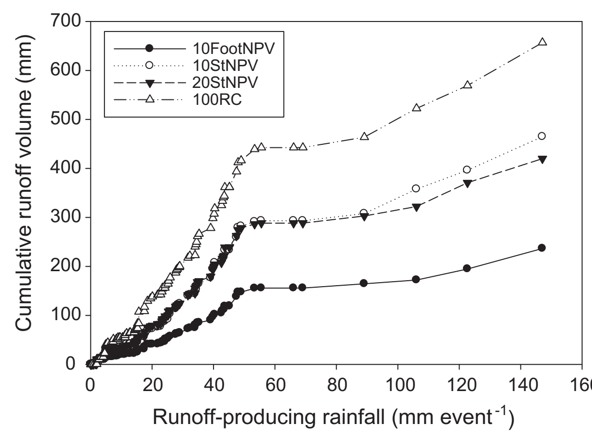

Fig. 4. Cumulative runoff sorted by rainfall event size (mm) for the 3 years studied (April–October). Each point represents the average of the three watersheds for each treatment (10FootNPV, 10StNPV, 20StNPV and 100RC).

Table 2
Maximum intensity of rain, total amount of water and the number of events that occurred in spring, summer and fall of 2008, 2009 and 2010.

	2008			2009			2010		
	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
Mean intensity (mm h^{-1})	37.3	40.1	20.5	15.2	15.5	11.2	18.5	40.4	5.3
Total volume (mm)	364.2	503.0	113.7	282.2	318.5	223.8	451.1	701.0	91.4
Events #	23	24	1	16	18	13	22	30	2

343 mm). Regardless of the different rainfall and runoff patterns of each year, we observed a trend in the percent reduction of cumulative runoff volume through the years due to the introduction of NPV (Fig. 5). On average, from 2008 to 2010 runoff was reduced by the three treatments with NPV by 29%, 44% and 46%, respectively. There were no significant differences among 10FootNPV, 10StNPV, 20StNPV and 100RC in 2008 and 2009 (Fig. 5). In 2010 we found significant differences ($p = 0.064$), with the 100RC treatment having the greatest cumulative runoff, 10FootNPV producing the least runoff while 10StNPV and 20StNPV were intermediate (Fig. 5). Repeating the same analysis comparing all the treatments with NPV considered as a single factor (10FootNPV, 10StNPV and 20StNPV) to 100RC watersheds, we found highly significant differences for all the events that occurred in 2010 ($p = 0.009$), with the 100RC treatment having the larger cumulative runoff than all the individual NPV treatments. Combining all 3 years we found significant differences among the watersheds with NPV treatments ($p = 0.083$), with 10FootNPV having lesser runoff than 10StNPV and 20StNPV which presented similar runoff values.

Surface runoff volume in the 10FootNPV treatment watersheds was consistently less than the 100RC treatment watersheds across the 3 years studied (≈64%). However, the runoff volume produced by the other NPV treatments varied by year, with the smallest decreases occurring in 2008 (3.4% and 19.5% for 10StNPV and 20StNPV, respectively) when compared to the 100RC treatment. When compared to the 100RC treatment the cumulative runoff in the 10StNPV watersheds was progressively reduced across years (27.3% and 37.0% in 2009 and 2010, respectively), whereas the reduction observed in the 20StNPV watersheds was greater in 2009 (44.9%) than in 2010 (35.9%) and lowest in 2008. Highly significant differences only occurred among the watersheds with NPV treatments (10FootNPV, 10StNPV, 20StNPV) using runoff rates ($p = 0.007$) and in crops dormant season small events ($p = 0.038$, data not shown).

The runoff rate ($l\ s^{-1}\ ha^{-1}$) showed similar trends as the cumulative runoff patterns among treatments (data not shown). The comparison of each watershed treatment showed no significant differences in 2008 and 2009, but in 2010 the individual NPV treatments had significantly smaller runoff rates than the 100RC treatment ($p = 0.004$).

Analysis of peak flow, time to the occurrence of the first peak in each event and the runoff coefficient revealed the same progressive reduction of watershed response to rainfall across years due to NPV introduction (2010, $p = 0.046$, data not shown). Peak flows and runoff coefficients were greater for the 100RC treatment than all other treatments, with the 10FootNPV, 10StNPV, and the 20StNPV being similar. The time to the occurrence of the first peak was shorter for 100RC than for the rest of the NPV treatments. The time necessary to produce runoff from the moment of precipitation onset showed only significant differences in 2010 ($p = 0.07$), with no significant differences in the other years (data not shown). The time necessary to produce runoff was shorter for 100RC than for the watersheds with NPV.

The effect of NPV on hydrologic response also varied in relation to event size and season. Over the 3-year study period, we observed a total of 12 large runoff events (5 in crops dormant season and 7 in crops active growing season) and 82 small runoff events (41 in both crops dormant season and crops active growing season). Despite the similar number of rainfall events in the two seasons, the events occurring in the crop active growing season produced larger runoff volume although the differences were not significant ($p > 0.1$, 325 mm on average for crops active growing season compared to 189 mm on average for the crop dormant season, data not shown). Generally, the other hydrological variables analyzed were also greater in the crop active growing season than in the crop dormant season, although clear trends only emerged for large runoff events (Fig. 6). Watersheds with NPV (10FootNPV, 10StNPV and 20StNPV combined) had significantly smaller runoff volumes than the 100RC treatment for crops dormant season. In crops active growing season 100RC runoff was significantly greater than watersheds with NPV for both high and small events (Fig. 6a). The runoff coefficient percent was less sensitive to the NPV effect and was only greater for the 100RC treatment when compared to the NPV treated watershed in the dormant season (Fig. 6b). The analysis of mean runoff rate revealed that this variable was also sensitive to the introduction of NPV in the watersheds. As occurred with the runoff volume and coefficient, there were significant differences for both low and large events in crops dormant season. In crops active growing season 100RC runoff rates were also significantly greater ($0.14\ l\ s^{-1}\ ha^{-1}$) than in watersheds with NPV ($0.055\ l\ s^{-1}\ ha^{-1}$) (Fig. 6c) but only for small events. Peak flow rate was significantly reduced by watersheds with NPV compared to 100RC only for small runoff events (Fig. 6d). The runoff reductions due to NPV presence compared to 100RC occurred in both seasons (crops dormant season $p = 0.005$ and crops active growing season $p = 0.041$). The onset of runoff occurred at a significantly earlier time in 100RC watersheds than in the NPV treatment watersheds, but these differences were only highly significant for small events in crops dormant season ($p = 0.035$, data not shown).

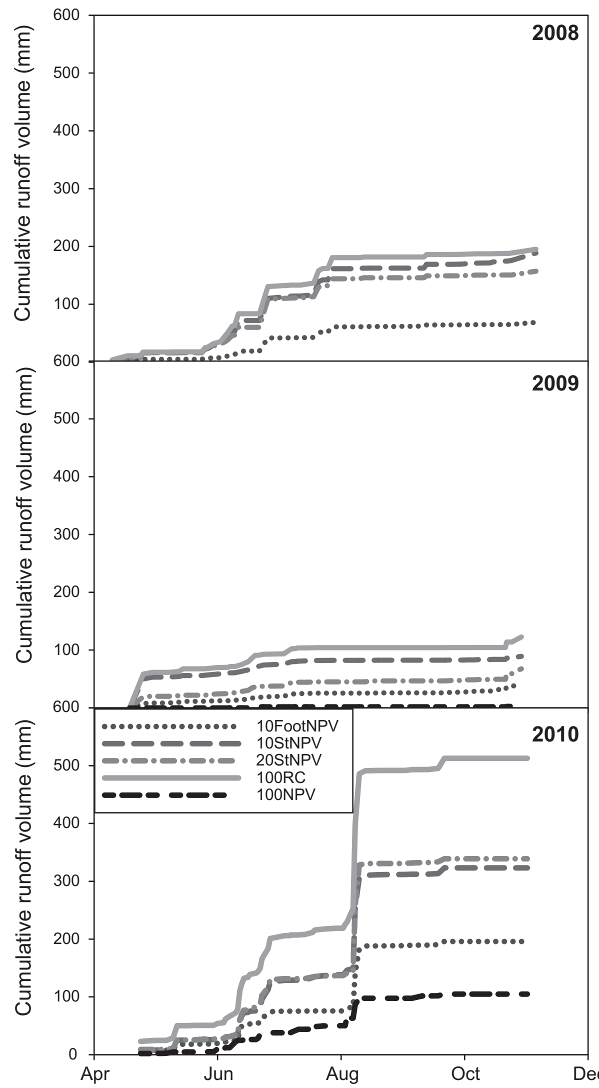

Fig. 5. Cumulative runoff volume (mm) from April to October in 2008, 2009 and 2010. Each line represents the average of the three watersheds for each treatment (10FootNPV, 10StNPV, 20StNPV, 100RC) and two watersheds in the case of 100NPV).

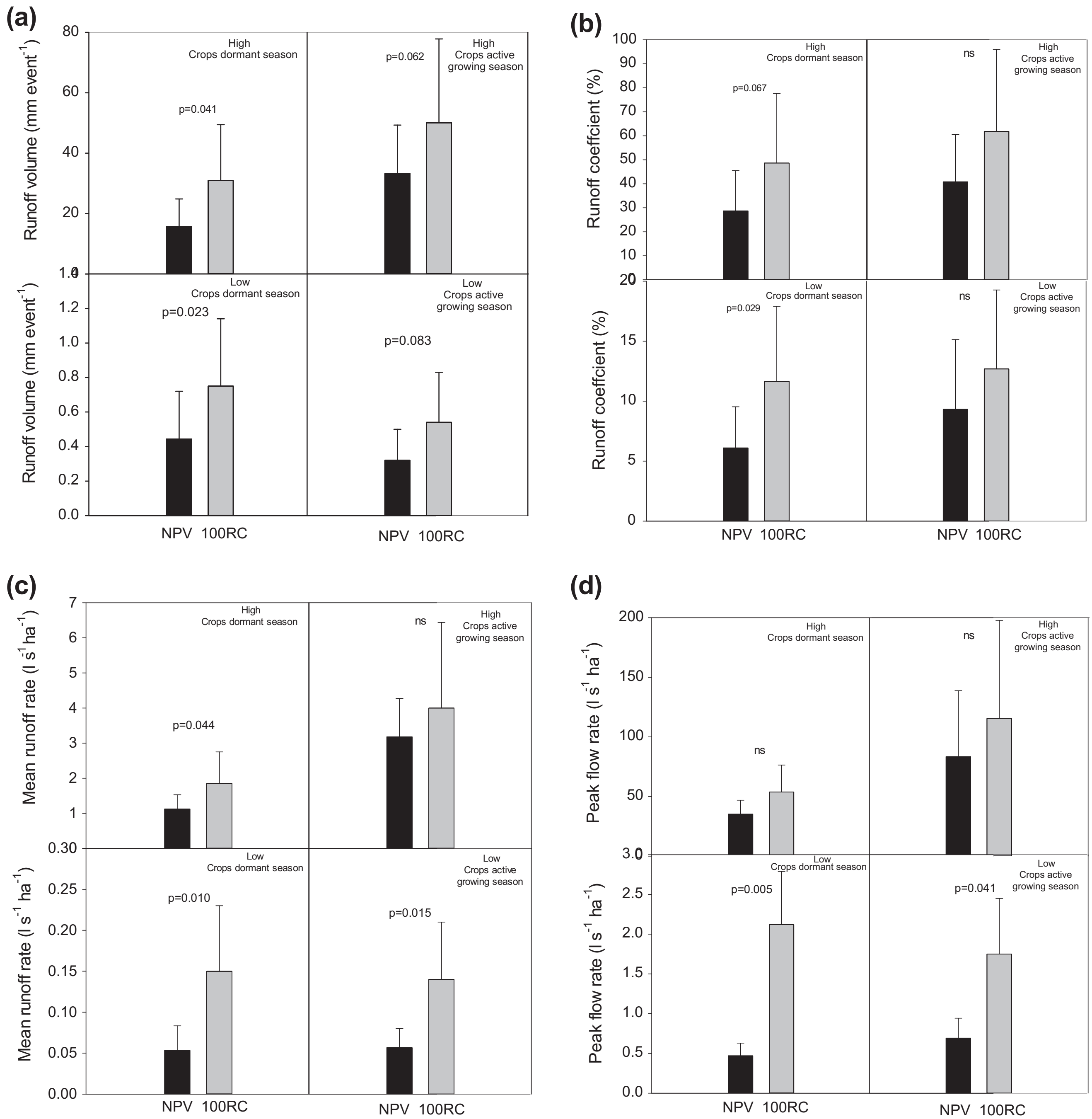

Fig. 6. Comparison between NPV treatments and 100RC of (a) mean runoff volume (mm event^{-1}), (b) runoff coefficient (%), (c) mean runoff rate (l s^{-1} ha^{-1}) (l s^{-1} ha^{-1}) and (d) peak flow rate (l s^{-1} ha^{-1}). The error bars represent 95% confidence intervals for the mean runoff. Actual values of p are shown, ns: no significant differences found.

The comparisons made throughout the series of figures in Fig. 6 were also completed with the inclusion of the 100NPV treatment for 2009 and 2010 (Fig. 7). Results showed that runoff volume registered in 100NPV was smaller than the NPV treatments and the 100RC in all cases except for the small events measured in the crop active growing season where there were no differences between NPV treatments and 100NPV.

4. Discussion

In this work, we demonstrated through the use of different watershed response measurements (runoff rates and volume) and other variables (runoff peak, runoff coefficient, time to first peak and time to onset of runoff), that the conversion of small areas of cropland to native prairie can produce significant ecosystem service benefits in terms of hydrologic regulation. Restitution of runoff dynamics in agricultural watersheds towards conditions present under native prairie vegetation can have positive effects on maintaining flood control and nutrient cycling processes, as well as reducing contaminant transport and erosion (Blanco-Canqui et al., 2004).

The average runoff reduction (37%) reported in our study over a 3 year period, comparing NPV watersheds with 100RC, is within the broad range of values reported by other similar studies in the U.S. Corn Belt region and central Canada. The introduction of small amounts of perennial vegetation in croplands reduced runoff from 1% (Udawatta et al., 2002) to 52% (Gilley et al., 2000). Differences in

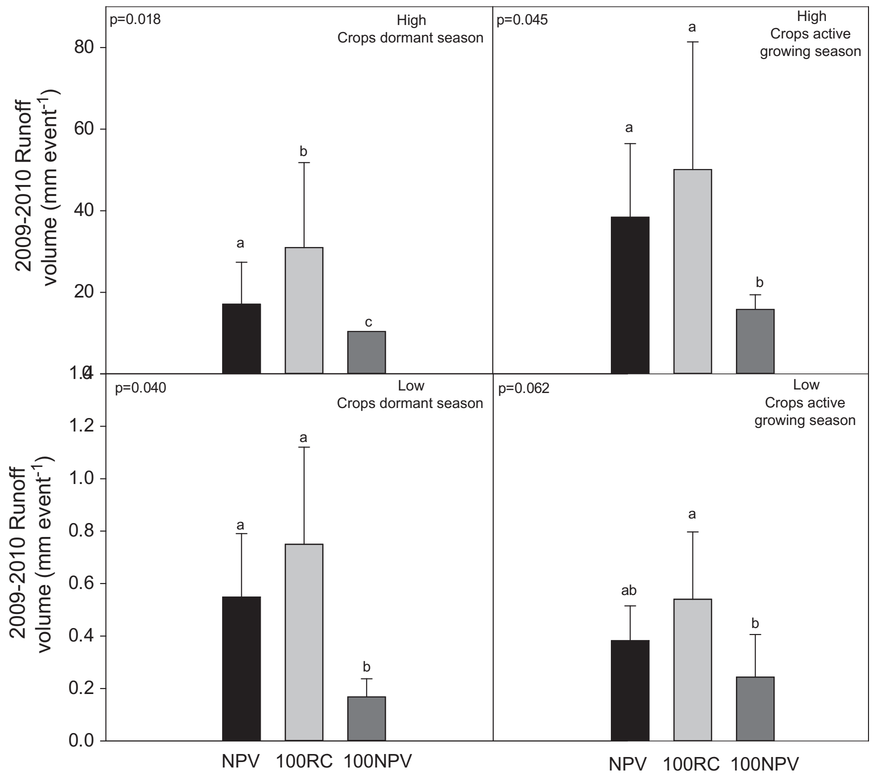

Fig. 7. Mean runoff volume (mm event^{-1}) for 2009 and 2010 for watershed with% of NPV, 100RC and 100NPV. Different letters indicate significant differences. Actual values of p are shown, Actual values of *p* are shown, ns: no significant differences found.

buffer width was identified as the main controlling variable (Abu-Zreig et al., 2004), while other factors such as treatment design (filter strip/grass barrier, Blanco-Canqui et al., 2004), agricultural practices (tillage-nontillage, Gilley et al., 2000), perennial treatment establishment (years after perennials seeding, Udawatta et al., 2002), and perennial types used (trees vs. grasses, Veum et al., 2009), likely also played a role.

The greatest runoff reduction consistently occurred in the 10FootNPV watersheds (Fig. 3–5). These differences were highly significant considering runoff rates and runoff volume in crops dormant season small events throughout the three study years. Significant differences were also reported for runoff volume in the last year of study. These findings demonstrate a slight interaction between NPV amount and position in the studied watersheds, since the same percentage of NPV (10% of the watershed) but with a different position and distribution (10StNPV) resulted in all cases in larger runoff relative to watersheds with 10% of NPV located at the foot position (10FootNPV).

Others have suggested that placing perennial vegetation on slopes should yield the greatest benefits for soil hydraulic properties, because slope areas are generally most vulnerable to degradation (e.g., Meyer and Harmon, 1989; Fu et al., 2011). In our study, other factors appeared to have a greater positive influence on runoff reduction, such that NPV at the footslope position was most effective. Our results are possibly related to a non-uniform distribution of flow and soil water content. The same percentage of NPV at the footslope or backslope have a different distribution, with the NPV filter strip being wider and shorter at the footslope and longer and narrower at the backslope (Fig. 1). Wider vegetated filters present a larger effective buffer area to reduce runoff export (Blanco-Canqui et al., 2006) despite having the same area as strips that are longer and narrower. Another important factor explaining the superior performance of NPV when located at the footslope position is that soil water content in agricultural watersheds without NPV is usually greater at the footslope compared to shoulder or backslope positions because of the greater contributing area for runoff (McGee et al., 1997). This non-uniform distribution of soil water content could make NPV at the foot position more effective in reducing runoff, thereby reducing soil water content (Brye et al., 2000) which could increase the potential for infiltration. Although in 20StNPV there were two out of three watersheds with 10% at footslope (Table 1), the third replication had 6.7% at footslope, with the 20NPV treatment on average having narrower NPV filter strips at the footslope position, and therefore having on average a smaller effective area than 10FootNPV. Differences in runoff generating processes, i.e., infiltration excess runoff from the backslopes vs. saturation excess runoff originating from the footslopes, may be contributing to the responses to these NPV treatments. This remains an area for future investigations.

The rainfall amount explained a significant proportion of the variation in runoff volume (Fig. 3). However, the percentage reduction in runoff volume was observed to be greater in 2010 than in 2009 and then again, in 2008 regardless of the very different rainfall patterns in each year studied (Fig. 2). We hypothesize that as NPV became better established, vegetation cover increased and roots of the vegetation occupied more soil volume (Udawatta et al., 2002) producing progressively greater runoff reduction. This argument agrees with the results of biomass sampling in the NPV strips (unpubl. data), demonstrating that biomass increased from 376 g m^{-2} in August 2009 to 572 g m^{-2} in August 2010. Thus runoff reductions may be even greater in the future as the NPV becomes more established. Similarly, Udawatta et al. (2002) found that most reductions occurred in the second and third years after treatment establishment, with no apparent runoff reductions observed the same year that treatments were applied, possibly due to initial soil disturbance and reduced evapotranspiration. Moreover, Tomer et al. (2010) found that the greatest improvement in shallow groundwater quality occurred within 3 years of prairie establishment at the 100NPV site and 2010 was the third year after establishment of the NPV strips. Conversion of cropland to perennial grasses could produce changes in runoff not only due to perennial establishment as explained earlier, but also because perennial vegetation produces changes in soil hydraulic properties. However, several years may be required before perennial vegetation is capable of substantially ameliorating changes in soil pore structure caused by tillage (Schwartz et al., 2003). Runoff reduction can also occur due to resistance to flow, ponding and greater infiltration. Reduction in flow velocity can also result from the physical resistance of the standing stems of the perennials plants (Meyer et al., 1995), ponding water upslope which favors sediment deposition (Melville and Morgan, 2001; Ziegler et al., 2006).

In general, the runoff reductions observed in the NPV relative to the 100RC watersheds were more pronounced in spring and fall (crops dormant season) compared to summer (crops active growing season) (Fig. 6). In these seasons, corn or soybean cover is either absent or minimal, and only becomes fully developed in the summer. In contrast, perennials maintain belowground tissue throughout the year, allowing them to initiate growth vegetatively in early spring. Annual crops must germinate from seed every spring, and therefore require more time to develop. Thus, a longer growing season by perennials causes a reduction in soil water content during critical periods such as spring and fall, which, in turn, can increase water infiltration and storage (Bharati et al., 2002; Anderson et al., 2009). However, in summer, water use by perennial vegetation and annual crops is generally similar, as demonstrated by a related work also conducted at the NSNWR measuring the water use (evapotranspiration). These measurements were based on Bowen Ratio techniques and taken in crops (corn) and a 5 year old prairie, whereby mean daily evapotranspiration rates recorded over a 4 month period in the peak growing season (July–August) were nearly similar (5.6 mm for prairie, and 5.8 mm for corn) (Mateos-Remigio et al., in preparation).

We only observed runoff volume differences between NPV and 100RC in crops active growing season for high rainfall events. The highest runoff events could minimize the NPV buffering capacity due to a progressive saturation of soil water content, given similar transpiration as the crop during the active growing season and the little difference between infiltration measurements in crop areas and NPV area in a preliminary on-site study. Runoff events resulting from saturation excess and high rainfall events have been reported for nearby watersheds (Sauer et al., 2005) and in other regions (Robinson et al., 2008). Continuously monitored water table levels at one of the watersheds (Interim-1) clearly showed that shallow groundwater had risen to close to or even higher than the ground surface for the entire watershed during the large storms from August 8–11, 2010, demonstrating the saturation excess runoff. Nevertheless, the events analyzed in crops active growing season as large events were not very frequent. We only registered 7 events, and 5 were observed in 2010 (Fig. 2). It has also been demonstrated that NPV treatments not only mitigated runoff during small events, but they were also helpful for large events reduction (Fig. 4). Reducing peak flow rates could be important for erosion and nutrient export reduction since it has been demonstrated that large flood events are important to the nutrient load to rivers, for example in Iowa (Hubbard et al., 2011).

There are also other external factors influencing runoff response including slope, watershed size, species composition and density of the vegetation, inflow rate and soil texture (Abu-Zreig et al., 2004; Liu et al., 2008). In our study, species composition, plant density, and soils are considered similar for every watershed. Size and slope did not produce significant differences in runoff response among watersheds (nonsignificant relationship between cumulative runoff for each watershed and slope and size, $p > 0.1$).

5. Conclusions

Our results indicate that small amounts of NPV (<20% NPV) strategically incorporated into corn–soybean watersheds in the Midwest found in dissected glacial (pre-Wisconsinan) terrain, can be used to effectively reduce runoff. The differences among the watersheds were attributed mainly to NPV amount, position, and establishment time. The differences in runoff reductions were greater in spring and fall (crops dormant season) due to the different perennial and annual phenology. Soil water saturation counteracted these differences during some periods. However, overall the NPV practices were effective during both small and larger events.

A slight interaction between size (10–20%NPV) and position (footslope vs. contour strips) of NPV strips was observed although differences among NPV treatments were not always significant. Converting 10% of cropland to NPV at the footslope position was the most effective design to reduce runoff and the easiest to manage, presenting the greatest hydrological benefits with the lowest lost income (percentage of cropland converted to NPV).

The observed decreases in runoff are especially interesting given the short time that the watershed treatments have been in place, and the progressive reduction observed across the 3 year study period. This could have long-term benefits for ameliorating negative impacts of annual crops agriculture on the overall hydrologic functions in landscapes, including other related processes (erosion, contaminants transport, etc.). The major runoff reductions were obtained in spring and fall, which are the most critical periods because of relative bare croplands soils.

More work is needed to explore the potential of these management practices under different environmental conditions, as well as in larger watersheds. Additionally, more information is needed to link these results to sediment and nutrient loss and contamination of groundwater, streams, rivers and oceans, water pollution, at larger scales. These practices could help to ensure flood control and water quality, services of high importance. Small income lost (croplands to NPV) could have important environmental benefits as demonstrated at a relatively small scale in this work.

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