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The potential to reduce runoff generation through improving cropping and tillage practices in a sub-humid continental climate

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ABSTRACT

Agricultural sustainability is threatened by both water deficit and water excess, especially at the presence of extreme meteorological events resulting from climate change. However, there has been lack of demonstrations on management options with long-term values for agricultural adaptation to runoff. Using 20 years of monitoring data (1993–2012) for two experimental fields in the Canadian Prairies as a case study, we quantified the effects of rainfall characteristics, crop type and biomass, and tillage on growing-season runoff generation using regression analyses and thereafter scenario comparisons. With growing-season gross rainfall ranging between 183 and 456 mm, runoff responses varied between 0 and 59 mm. Over the 20-year study period, 70%–74 % of the growing-season runoff was generated by rainfall events >100 mm. Compared to high-intensity tillage, long-term conservation tillage reduced both overall runoff and runoff in large events likely by improving water infiltration. Under both tillage methods, growing-season runoff significantly increased with increasing rainfall but decreased with increasing biomass (R^2 range: 0.40–0.58; p range: 0.0007–0.02). At the event level, the rainfall-runoff relationship followed a piecewise regression model ($C_d = 0.82$; $p < 0.0001$; "breakpoint" rainfall event = 105 mm), in which runoff increased slowly before reaching the "breakpoint" but rose sharply afterwards. Due to a greater biomass, canola resulted in less runoff than wheat. Scenario analyses showed that increasing crop biomass by 50 % under the current average rainfall conditions could reduce runoff by 81–86 % in wheat and 100 % in canola. The reduction may be attributed to the combined effects of crop on interception, evapotranspiration, and infiltration. In conclusion, although in a sub-humid continental climate like the Canadian Prairies there are generally low amounts of rainfall runoff, this study demonstrates significant runoff in some years, especially following large rainfall events. Runoff generation can be significantly reduced through improving cropping and tillage practices, and such effects on regional water retention should be further assessed by considering the past and future changes in climate and management.

1. Introduction

In many regions worldwide, the sustainability of agriculture is threatened by both water deficit and water excess [1], especially in the presence of extreme meteorological events resulting from climate change [2,3]. These regions include the Canadian Prairies, which have a climate ranging from semi-arid to sub-humid continental. The Canadian Prairies consists of the provinces of Manitoba, Saskatchewan and Alberta, with a total area of 1.78 million km^2. Although this region is known for relatively low precipitation (around 300–600 mm in most places [4]), it has high organic matter soils and warm summers and is one of the most important cereal and oil crop production regions in the world. It accommodates 85 % of the national field-crop area and produces 95 % of total wheat (*Triticum aestivum* L.) and almost all canola (*Brassica napus* L.)

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in Canada [5]. Like many other regions in the world, nutrient losses through runoff from agricultural land are among the main contributors to eutrophication of many water bodies, such as Lake Winnipeg [6].

Past work has confirmed that most runoff in the Canadian Prairies is driven by snowmelt [7–9]. However, there has been an increasing amount of evidence that rain-derived runoff plays a dominant role in some years [8,9], suggesting the need to reduce nutrient losses through this pathway, especially in the context of climate change that is expected to lead to greater and more rain and runoff events [10,11]. While past field-scale water quality research in the Canadian Prairies has largely focused on snowmelt runoff [12–14] and/or on a source management perspective [15–17], more research is needed to explore options for reducing the generation of rainfall runoff.

Crops are a key component of the hydrological cycle influencing rain interception, evapotranspiration and infiltration [18]. Rain interception means that when rainfall occurs, part of the rain is intercepted by crop canopy or residue and becomes ineffective for runoff generation. The difference between gross rain and the interceptive rain loss is defined as effective rain [19]. Due to their influences on rain interception, evapotranspiration and infiltration, crops have a large potential to affect rainfall runoff. For example, a field-plot rain simulation study in Alberta showed that perennial forage generated less runoff than fallow or an annual crop in most cases, due to its denser coverage and longer growing season [20]. It also showed that growing barley (*Hordeum vulgare* L.) in rows perpendicular to a slope reduced runoff more than in the rows parallel to the slope [20]. Another Alberta rain simulation study found that native grasses (*Stipa—Bouteloua—Agropyron* spp.) and Russian wildrye (*Elymus junceus* Fisch.) reduced runoff by more than 50 % as compared to wheat and crested wheatgrass (*Agropyron cristatum* L.) [21]. In Manitoba, alfalfa (*Medicago sativa* L.) was found to generate much less runoff than wheat and corn (*Zea mays* L.) [22]. Some of the differences between crops may result from rainfall interception by the canopy [19, 23]. However, quantitative analyses on why and how different types of crops affect rainfall runoff are still lacking. Moreover, although tillage is regarded to affect runoff by influencing depressional water storage on the soil surface, rain interception and water infiltration, few studies have demonstrated the runoff effects directly [18,24]. Therefore, impacts of crop and tillage management on rainfall runoff need to be further investigated.

In the last several decades, the Canadian Prairies have experienced detectable changes in rainfall patterns [10] and dramatic changes in crop production [25] and tillage [26]. For example, the area seeded to canola has increased from <2 million hectares in the 1970s to about 9 million hectares in recent years and yields of canola and wheat per unit area have almost doubled. Changes are ongoing and will likely continue. For example, summer rainfall was predicted to increase by up to 10 % across the Prairies during 2081–2100 as compared to 1986–2005 under the low emission scenario (RCP2.6) but a decreasing rainfall by up to 10 % in most Prairie crop production regions under the high emission scenario (RCP8.5) [11]. Yield of spring wheat was predicted to increase by 20 % in 13 locations across the Prairies during 2041–2070 as compared to 1971–2000, using seven climate scenarios under two emission scenarios of RCP4.5 and RCP8.5 (without considering the future improvements in crop breeding and management) [27]. Past changes have likely affected runoff hydrology and nutrient loss, and future changes are anticipated to continue playing a critical role in these dynamics. However, the effects have not been properly assessed and quantified.

Using 20 years of rainfall, crop and tillage management, and runoff data from Manitoba, we examined the patterns of rainfall and runoff and, more importantly, the effects of rainfall, crop and tillage on runoff generation and reduction through developing regression models and, thereafter, using them in scenario analyses. Our specific objectives were to: (1) characterize patterns of rainfall and runoff, including large events, (2) understand the effects of rainfall characteristics and crop and tillage management on runoff generation under current and changing climate and management conditions, and (3) examine the impacts of rain interception by crop on effective rain and runoff.

2. Materials and methods

2.1. Study site

The study was conducted on two experimental fields in southern Manitoba, Canada (49°20′ N, 98°22′ W; Fig. 1). This area has a sub-humid continental climate, with a long-term mean annual temperature of approximately 3 °C and mean annual precipitation of 550 mm during 1979–2009 [28]. About 60 % of the precipitation occurs during the growing season, i.e., from May to September. Soils are primarily clay-loam formed on moderately to strongly calcareous glacial till that overlays shale bedrock, with dominant soil series as Dark Gray Chernozems (Mollisols). The experimental fields are adjacent, both are north facing, have the same soil and similar sizes (4.2 and 5.1 ha, respectively). Both fields have undulating landscapes and slope gradients of approximately 5 %. They are considered good paired fields [15]. The fields were established in 1992 and have been used for studying the effects of tillage [12,15] and soil phosphorus management [17] on nutrient losses in snowmelt and rainfall runoff.

During 1993–2012, the fields were used for producing cereals and oilseeds, with wheat–canola in most years and flax (*Linum usitatissimum* L.), oat (*Avena sativa* L.) or barley for the rest, typical of the Canadian Prairies. The crops were generally seeded in mid-May and harvested in late August or September. Thus, we defined the growing season as May to September and focused our study on this period. The fields had the same crop over the entire study period but different tillage methods in the years 1997–2007 and 2009, during which one field was consistently tilled more intensively (hereby named as High-intensity tillage field, Field-H) than the other (Low-intensity tillage field, Field-L). In other years, they had the same tillage. In Field-H, intensive tillage that usually involved a heavy-duty cultivator in fall and a light-duty cultivator and/or harrow/packer in spring was used in 16 years, and non-intensive tillage with a light-duty cultivator in fall or spring in four years. In contrast, Field-L received high-intensity tillage for six years, light-duty cultivation for two years, harrowing for six years, and no-till (direct drilling) for six years. Based on the tillage similarities and differences between the fields, the 20 years were divided into periods of pre- (1993–1996), early- (1997–2001), late- (2002–2007) and post-tillage (2008–2012). The tillage method used prior to 1993 is unknown but likely intensive in both fields, as high-intensity tillage was common before the mid-1990s [29]. Each year, information on grain yield was collected from the producer. The yield data were used for estimating straw biomass production, using straw:grain dry weight ratios of 1.34 for spring wheat [30], 2.33 for canola [31], 1.44 for oat [32], 1.02 for barley [33], and 1.94 for flax [34]. Detailed information on crop types, tillage methods, grain yield and straw biomass is summarized in Table S1.

2.2. Monitoring and analyses of gross rainfall, effective rainfall and runoff

Gross rainfall was monitored on-site throughout the study period using a tipping-bucket rain gauge. A rainfall event was identified (and quantified) when rain fell on either a single day or multiple consecutive days, with separation between events by a minimum of three no-rain days. That is, rainfall events were divided when there were three or more no-rain days between two rainy days. The use of this event characterization method was to account for the influence of antecedent rain on the subsequent runoff. Runoff was monitored in each field, by continuously measuring the water levels using an ultrasonic sensor and recording it with a data logger at a compound angle V-notched weir that was installed at the lower edge of the field (Fig. 1). The water levels were then converted to flow rates at 5-min intervals using a standard V-notched weir flow equation [35], which were eventually calculated into daily runoff depth for the entire field in mm. A runoff event was defined as runoff that occurred during/following a rainfall event. Daily rainfall

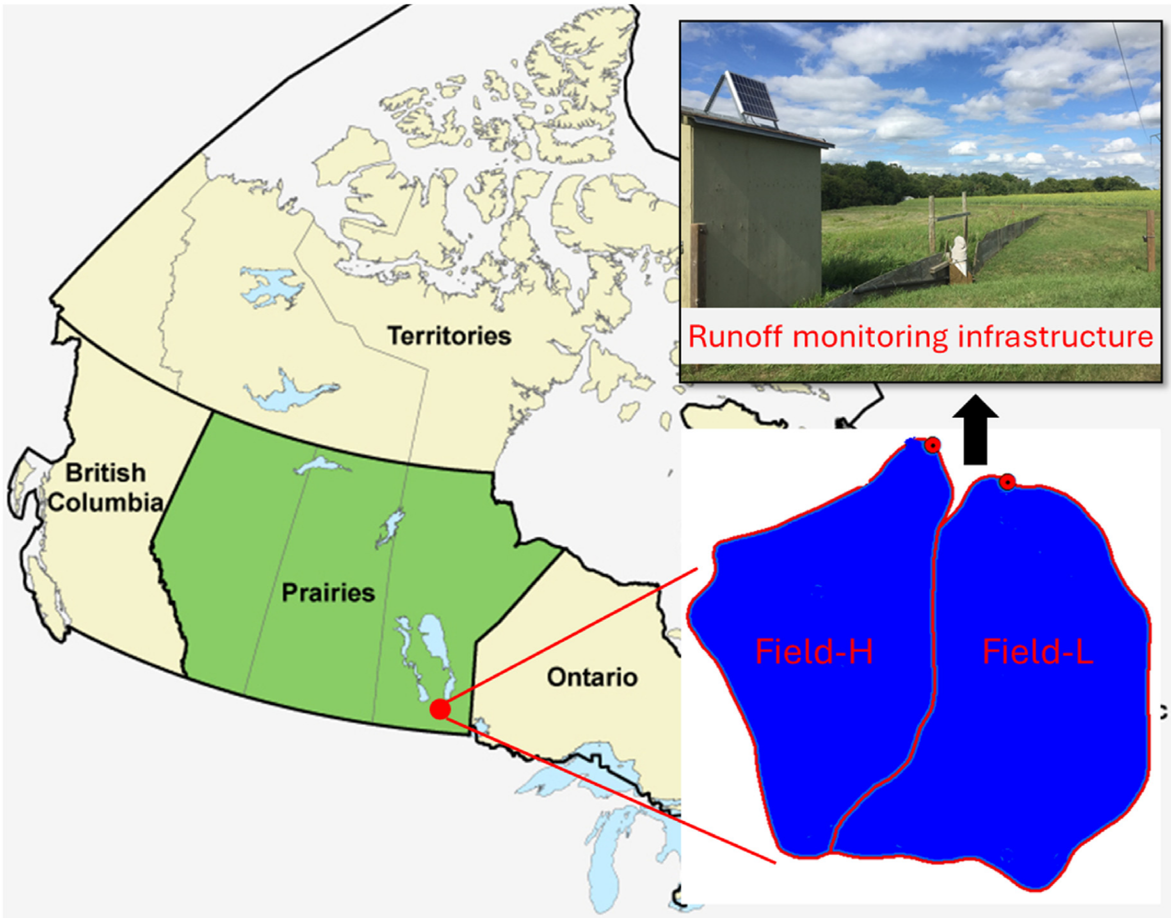

Fig. 1. Geographical locations of the Canadian Prairies in Canada and the study site within the Prairies. The two experimental fields were similar in many ways except that Field-H was intensively tilled and Field-L had conservation tillage or no-till for most years. Runoff was monitored during 1993–2012 at the lower edge of each field.

and daily runoff were summed up to obtain event, monthly and growing-season level total rainfall and total runoff, respectively. Runoff coefficients were calculated as the ratio of runoff depth to the corresponding rainfall input for a given event or time period.

Daily effective rain was estimated by deducting interceptive rain loss by crop canopy from the measured daily rain amounts. The daily rain interception storage capacity (RISC) of crop canopy was modelled as a function of the leaf area index (LAI) using the Von Hoyningen-Huene model [36]. Several models are available in the literature for modeling RISC [37,38], but none has been derived in the Canadian Prairies. The Von Hoyningen-Huene model was chosen, because it was previously confirmed to be more suitable for climates like the Prairies [38]. Daily LAI was previously modelled in Manitoba at a site about 40 km away from ours, as a function of day of year (DoY) for spring wheat, canola, oat, corn and soybean (*Glycine* max L.) [39]. Here, we modelled daily RISC by integrating the Von Hoyningen-Huene model [36] and the Manitoba model [39]. The Manitoba model for spring wheat was applied to barley and flax. In addition to crop canopy, crop residue can also result in interceptive rain loss. At a single event level, RISC of crop residue was previously modelled by Savabi and Stott [40] as a function of residue mass for wheat, corn and soybean in the mid-west United States, and another model developed by Arreola-Tostado [41] was recommended for other crops [38]. In the present study, the lack of information on the temporal changes in residue mass made it impossible to model the daily RISC of crop residues for quantification of cumulative interceptive rain loss during the growing season. However, the models of Savabi and Stott [40] and Arreola-Tostado [41] were useful for estimating RISC under known residue mass to understand the potential interceptive rain loss by the residue.

All models used for modeling RISC of crop canopy and residue are summarized in Table S2. Daily interceptive rain loss and effective rain were estimated as follows:

$$R_{eff} = R_{gross} - R_{int} \quad (1)$$

Where R_{eff} is daily effective rain (mm), R_{gross} is total daily rainfall (mm), and R_{int} is the volume of rain intercepted by vegetation (mm). When $R_{gross} \geq$ RISC, R_{int} = RISC; otherwise, $R_{int} = R_{gross}$. The estimations were based on the assumptions that throughfall and stemflow were negligible until daily gross rain exceeded RISC and that the maximum daily interceptive rain loss equalled RISC. Daily interceptive rain loss and daily effective rain were accumulated to obtain event, monthly and growing-season level values for a better disentangling of factors influencing runoff.

2.3. Modeling effects of rainfall, tillage and crop on runoff

Effects of rainfall, tillage and crops on runoff were analyzed using regression models (described below). Tillage effects were assessed by comparing runoff coefficients between Field-H and Field-L for the events with runoff depth >0 mm in either or both fields. The assessment was done for all periods enabling pre-, early-, late-, and post-tillage comparisons. Moreover, the relationship between the differences in runoff depth (Field-L minus Field-H) and rainfall depth for the events that occurred during the periods of late- and post-tillage comparison (i.e., 2002–2012) was fitted to a linear model. The combined effects of rainfall and crop on growing-season runoff were assessed separately for years with high-intensity tillage and years with lower-intensity tillage using multiple linear regression models. The rainfall-runoff relationship was further analyzed at the event level, and crop effects were explored by fitting the relationship between growing-season level runoff coefficient and crop straw biomass or total biomass to logarithmic models. The fit of all models was tested using SAS 9.4 at a significance level of 0.05 [42].

2.4. Scenario analyses to estimate the impacts of changing rainfall, tillage and crop production on runoff

Based on the regression models developed above, we assessed the potential effects of variability in rainfall, changing tillage and crop production on runoff at both the growing season and event levels through scenario analyses. Scenarios for the growing-season assessment included: (1) current average rainfall and production level (baseline), (2) an increase in growing-season rainfall by 20 %, (3) a decrease in rainfall by 20 %, (4) an increase in crop production level by 50 %, (5) a decrease in crop production by 20 %, (6) an increase in rainfall by 20 % and an increase in crop production by 50 %, and (7) a decrease in rainfall by 20 % and a decrease in crop production by 20 %. The values of the changes in rainfall and crop production were chosen based on future projections by others [11,27], however, higher values were used to obtain a "scoping" assessment. All the scenarios were assessed for wheat and canola, with high- and low-intensity tillage separately.

The rainfall event level scenarios were used to further clarify the effects of changing gross rainfall and tillage methods on runoff under conditions with different sizes of rainfall events. In the rainfall scenarios, an increase in growing-season rainfall by 20 % was tested, which is equivalent to an increase of 65 mm of rain for the averaged growing-season rainfall amount of 325 mm during the 20-year study period. The scenarios were designed to test different distributions of the increased rain amount, as (1) many small events with rainfall <25 mm per event, (2) an extra single, 65-mm rain event, (3) an addition to a 25-mm rainfall event (added to an averaged event), and (4) an addition to a 150-mm rainfall event (added to a large event). In the tillage scenarios, tillage was changed from high-intensity tillage to conservation tillage for (1) a 50 mm rainfall event and (2) a 150 mm event. In all rain, crop biomass or tillage scenarios, we assumed that other conditions remained unchanged.

3. Results and discussion

3.1. General patterns of gross rain, effective rain and runoff

In the Canadian Prairies, the growing season is generally shorter than in many other regions with similar latitudes and/or altitudes due to a continental climate and a strong influence of the polar vortex [7]. During the 20 growing seasons of this study, cumulative gross rain at our study site ranged from 183 mm in 2006 to 456 mm in 1993 (Table S1), with an average of 327 mm. Correspondingly, cumulative runoff varied from 0 mm in nine out of 20 years to 58.5 mm in the intensively tilled Field-H and to 34.7 mm in the less intensively tilled Field-L both in 2005

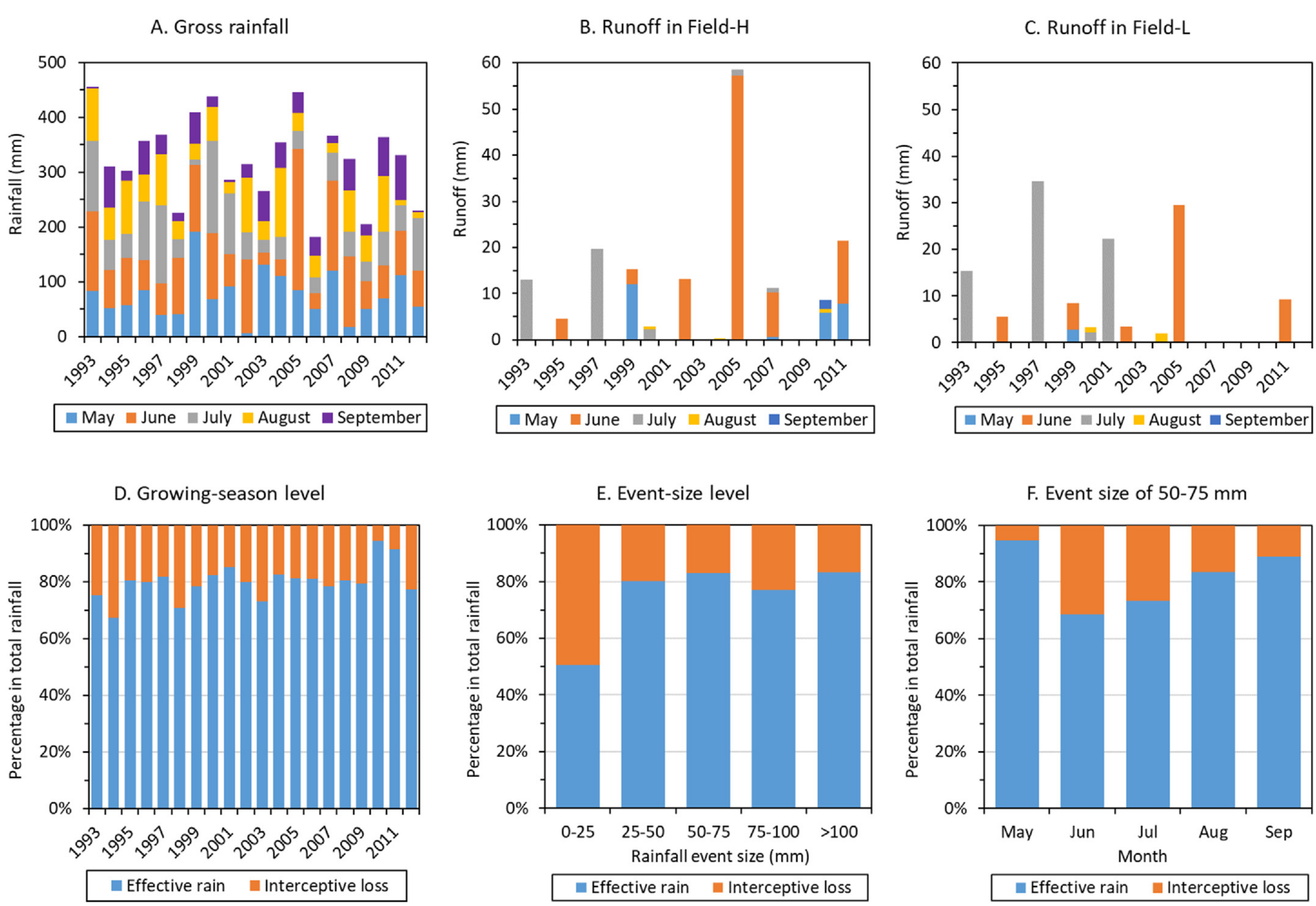

Fig. 2. Distribution of rainfall and runoff over the 20 study years: (A) monthly gross rainfall, (B) monthly runoff from the intensively tilled Field-H, (C) monthly runoff from the non-intensively tilled Field-L, (D) growing-season level percentages of interceptive rain loss by crop canopy and effective rain in gross rain, (E) percentages of interceptive rain loss and effective rain under different sizes of rainfall events, and (F) percentages of interceptive rain loss and effective rain in different months for the event size of 50–75 mm as an example. Note that there was no runoff in some months and years.

(Table S1). Runoff coefficients ranged from 0 to 0.131 in Field-H and from 0 to 0.094 in Field-L (Table S1), confirming the overall low runoff generation potential in this region [8,9]. Gross rain (Fig. 2A) and runoff in both Field-H (Fig. 2B) and Field-L (Fig. 2C) varied widely by year and month, suggesting a large temporal variability of rain distribution and consequently of runoff generation.

Interceptive rain loss by crop canopy was estimated to account for 5–33 % of the gross rain over the 20 years, resulting in 67–95 % of the gross rain as effective rain (Fig. 2D). The loss was most significant during small rain events, and it accounted for roughly 50 % of the total rainfall for such events with 0–25 mm rain (Fig. 2E). In the events with >25 mm rain, its percentage of gross rain was about 20 % (Fig. 2E). The percentages of interceptive rain loss also varied with months, with greater values in June to August (when crops had larger biomass to intercept rain) than in May and September (Fig. 2F).

Overall, neither Field-H nor Field-L had many runoff events each year. Notably, however, runoff frequencies and amounts at the event level generally increased with increasing amounts of rain in the events in both fields (Table 1). Although about 65 % of the rainfall events had rainfall amounts smaller than 25 mm, they did not produce runoff in either field. In contrast, the events with >100 mm of rain produced runoff in almost all the events in both fields and the runoff amounts in these events accounted for 70 % or 74 % of the total runoff measured throughout the study period. The results stress the critical contribution of large (extreme) events to runoff. In the context of climate change, which is expected to result in more frequent and intense summer storms [11], management efforts are needed to target runoff reductions in such events.

3.2. Effects of rainfall, tillage and crop on runoff

Runoff generation is a complex process that is affected by meteorological variables (i.e., rainfall), topographic and soil characteristics [43], and land use, cover and management [44]. Multiple linear regression analyses demonstrated that rainfall and crop biomass together significantly affected growing-season runoff under both tillage systems (Table 2). When gross rain or effective rain, and total biomass or straw biomass, were used as independent variables, runoff consistently increased with increasing rainfall and decreased with increasing biomass, with the trends in individual variables statistically significant in most cases and the entire models significant in all cases (R^2 range: 0.40–0.58; p range: 0.0007–0.02). The results highlight the potential of crop management for managing runoff. It should also be noted that the regressions only explained about half of the variations. The rest of the variations could be partially due to the fact that rainfall distribution also affected runoff generation (Table 1). More is discussed below in 3.2.1.

Overall, the years with high-intensity tillage had better fits than the years with lower-intensity tillage (Table 2). This was likely because the non-intensive tillage group consisted of different types of tillage, i.e., light-duty cultivation, harrow and no-till, which may produce more complex effects on hydrology than the high-intensity tillage group with more consistent operations. In some cases, the models using effective rain slightly improved the prediction of runoff as compared to those using gross rain. However, the models with gross rain are similarly acceptable and, in practical terms, generally preferred for the Canadian Prairies, because estimations of interceptive rain loss may introduce errors and are not generally transferrable to other sites.

Table 1
Frequencies and ranges of rainfall runoff in relation to different event sizes of gross rainfall in the intensively tilled Field-H and the non-intensively tilled Field-L over the 20-year study period.

Fields	Rainfall ranges (mm event^{-1})	Events of runoff/ events of rainfall	Runoff ranges for the events with runoff (mm)	Runoff percentages in total runoff of all events (%)
Field-H	0–25	0/165	n.a.	0
	25–50	6/51	0.1–4.5	5.6
	50–75	7/25	0.3–13.6	17.2
	75–100	2/9	0.6-5.2	3.4
	>100	8/9	2.3–51.9	73.8
Field-L	0–25	0/165	n.a.	0
	25–50	4/51	0.1–5.5	6.4
	50–75	5/25	0.04–8.9	9.0
	75–100	3/9	0.05–19.6	15.1
	>100	7/9	2.1–29.0	69.6

Rainfall events totaled 259 in each field.

3.2.1. Rainfall-runoff relationship

The rainfall-runoff relationship is often nonlinear [45], due to other influential factors as discussed above. For all rainfall events that had similar tillage (i.e., the events that occurred during 1993–2012 in Field-H and during 1993–1996 in Field-L before tillage systematically changed), the gross rainfall-runoff relationship followed a piecewise regression (C_d = 0.82; p < 0.0001) [46], in which runoff potential generally remained very low at rainfall amounts of <105 mm per event but consistently increased (rather sharply) with increasing rainfall amounts for the events with >105 mm rain (Fig. 3A). Notably, the use of effective rain resulted in an even more significant rain-runoff relationship (C_d = 0.89; p < 0.0001; Fig. 3B) than when gross rain was used (Fig. 3A). This suggests that interception affects runoff. However, given 70%–74 % of the runoff occurred during large rainfall events (>100 mm event^{-1}, Table 1) and that the maximum daily interceptive rain loss was 4 mm, the magnitude of interception effects on runoff may depend on the duration (number of the days) and other climatic conditions of the rainfall event.

It should be noted that although the event-level rainfall-runoff relationship explained 82 % (using gross rain) or 89 % (using effective rain) of the variance, it did not capture some of the runoff events that were associated with 40–80 mm rain (Fig. 3A and B). Although most of the events in this range did not produce runoff, some generated 5–15 mm as shown by the four blue and two orange data points that are deviated from the first line of the piecewise regression in Fig. 3A. All these events were found in May and June when rainfall amounts were considerable, but this was also a time when crops were small and could not use much water. The deviation may be partially (or even largely) explained by antecedent soil moisture conditions, which affect water infiltration and saturation in the soil and, thus, runoff generation [47,48]. In 2011, for example, three runoff events occurred in Field-H, following 60 mm rain in May, 52 mm in May/June, and 52 mm rain in June, respectively. Nevertheless, a rainfall event of 70 mm in September did not generate any runoff. This trend was also well illustrated by daily rainfall-runoff dynamics (Fig. 3C), in which peaks of runoff and rainfall were frequently asynchronous. In the event of late June, which was not the largest (with only a rainfall peak of 35 mm), it resulted in the greatest runoff peak (13 mm) due to the wet soil resulting from previous rain (an approximate 150 mm rain in 30 days prior to the 35 mm rain event) increasing soil saturation and Hortonian runoff [49]. In contrast, when 70 mm of rain fell on the dry soil in September (with only 10 mm of rain in the previous 30 days), no runoff was generated. The results emphasize that although runoff amounts generally increase with increasing amounts of rainfall, the runoff potential of individual events was, as expected, also highly affected by antecedent soil moisture conditions. Also, a greater interception effect of the increase in plant surface biomass on rainfall in the later part of the growing season might have also contributed to the absence of runoff in September.

3.2.2. Tillage effects

Tillage greatly influenced runoff as demonstrated by its impacts on event-level runoff coefficients (Fig. 4A). During the pre-tillage period (1993–1996) when both fields had the same tillage, Field-L consistently had greater runoff coefficients than Field-H, which reflects the likely inherent runoff generation potential of the fields. However, when contrasting tillage methods were used during the early- and late-tillage

Table 2
Multiple linear regressions for modelling growing-season runoff (mm) as a function of rainfall (mm) and crop biomass production (Mg ha^{-1}) for years with high-intensity tillage and years with non-intensive tillage, respectively.

Tillage categories	X1	X2	Model	X1		X2		X1 & X2	
				R^2	*p*	R^2	*p*	R^2	*p*
Years with high-intensity tillage (n = 20)	**Gross rain**	**Total biomass**	**Y = 0.083X1 – 2.71X2 – 0.69**	**0.32**	**0.01**	**0.22**	**0.01**	**0.53**	**0.002**
	Gross rain	Straw biomass	Y = 0.084X1 – 3.81X2 – 2.47	0.32	0.01	0.24	0.007	0.56	0.001
	Effective rain	Total biomass	Y = 0.098X1 – 2.97X2 + 2.02	0.29	0.01	0.26	0.006	0.55	0.001
	Effective rain	Straw biomass	Y = 0.099X1 – 4.15X2 – 0.09	0.29	0.003	0.29	0.01	0.58	0.0007
Years with non-intensive tillage (n = 18)	**Gross rain**	**Total biomass**	**Y = 0.046X1 – 2.30X2 + 6.88**	**0.09**	**0.14**	**0.37**	**0.007**	**0.46**	**0.01**
	Gross rain	Straw biomass	Y = 0.051X1 – 2.80X2 + 1.96	0.11	0.12	0.29	0.02	0.40	0.02
	Effective rain	Total biomass	Y = 0.064X1 – 2.28X2 + 5.22	0.14	0.05	0.37	0.007	0.51	0.004
	Effective rain	Straw biomass	Y = 0.070X1 – 2.82X2 + 0.63	0.17	0.046	0.29	0.02	0.46	0.01

Non-intensive tillage includes light-duty cultivation, harrow and no-till. For practical reasons as explained in the text, the models **in bold** were chosen for the subsequent scenario analyses.

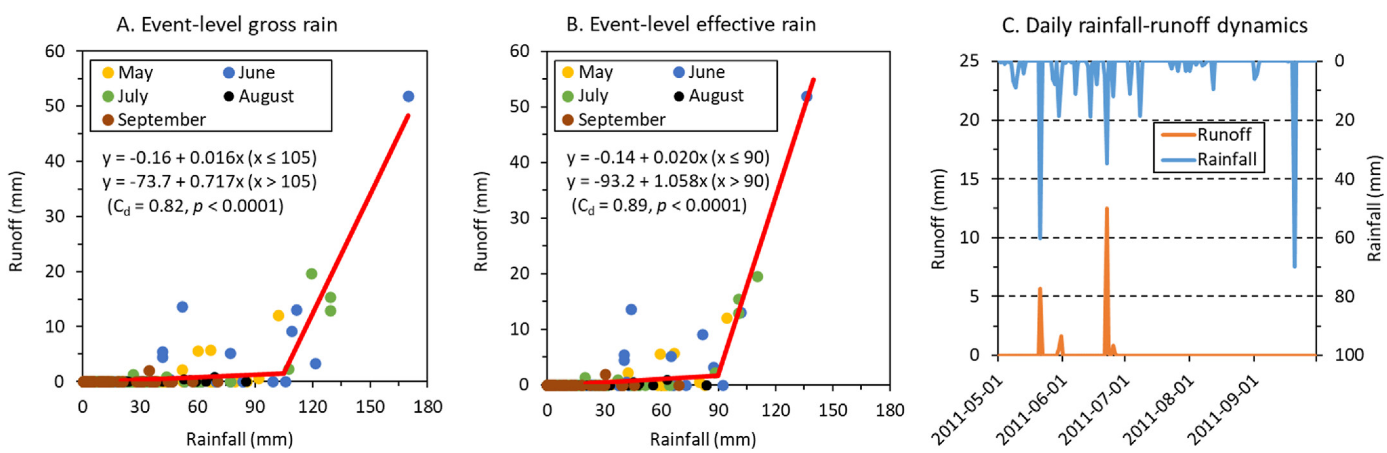

Fig. 3. Rainfall-runoff relationship. (A) Event-level gross rain and runoff relationship for all rainfall events under similar tillage practices (1993–2012 for Field-H and 1993–1996 for Field-L, n = 309). C_d is the coefficient of determination for the piecewise regression. (B) Event-level rainfall-runoff relationship developed using effective rain. (C) Daily gross rain and runoff relationship for the period of May 1 – September 30, 2011 in Field-H, which demonstrates an example of how antecedent rain, in addition to rain peaks, affects runoff generation.

periods (1997–2007), i.e., high-intensity tillage in Field-H versus less intensive tillage or no-till in Field-L, Field-L began to have smaller runoff coefficients than Field-H in some events during the period of early tillage-comparison (1997–2001) and in almost all events during the period of late tillage-comparison (2002–2007). The trend continued through the post-tillage period (2008–2012). The overall trend suggests that the repeatedly low-intensity tillage and no-till in Field-L converted the field from initially having greater runoff generation potential than Field-H to a field with smaller runoff potential.

Tillage affects runoff in various ways. Over the short term, the effects of tillage are two-sided. On one hand, it creates depressional storage [50], which increases water retention on the soil surface and thus reduces runoff [18]. On the other hand, when tillage incorporates crop residue into the soil, it diminishes the capacity of the vegetation to intercept rain and potentially results in more runoff [18]. Thus, the overall short-term effect likely depends on the balance between the tillage effect on depressional storage and the effect on rain interception, which may explain the confounding results of runoff coefficient comparisons during the early-tillage period (1997–2001) (Fig. 4A). In tillage management, thus, it appears an important issue regarding when tillage (of various types) should be carried out relative to the rainfall season and growing season – immediately post-harvest (August), late season post-harvest (October) or spring pre-seeding (April–May). Over the long term, however, low-intensity tillage and no-till decrease runoff potential by increasing infiltration of rain into the soil through its improvement on soil structure and porosity by increasing soil organic matter content, as observed in other studies [24,51–53], resulting in lower runoff coefficients than high-intensity tillage does. Moreover, the reduction in runoff amounts by low-intensity tillage and no-till increased significantly with increasing rain amounts ($R^2 = 0.76, p < 0.0001$; Fig. 4B), suggesting that reduced tillage over the long term could be an effective approach to reducing runoff in large (extreme) rain events.

3.2.3. *Crop effects*

This study provides data-based evidence that crops affect runoff generation in both intensively tilled Field-H and non-intensively tilled Field-L. The effects were similar for both fields, and results are presented only for Field-H (Fig. 5). In the years with runoff, growing-season level runoff coefficients significantly decreased with increasing crop straw biomass and total biomass, both following a logarithmic pattern (Fig. 5A and B). Although there were no true comparisons between crops, as no pairs of different crops were grown under exactly same rainfall conditions, canola had a smaller runoff potential than wheat, consistent with their reverse ranking in straw biomass (Fig. 5A) and total biomass (Fig. 5B). In addition to a greater biomass, canola also had a greater maximum daily LAI than wheat (6.7 versus 5.5). Across the study period, canola and wheat were each grown for seven years and they on average received similar amounts of gross rain during the growing season (314 and 315 mm per year, respectively). Among these years, four wheat years and three canola years had no runoff; however, in other years, wheat had consistently greater runoff coefficients (0.03–0.07) than canola (0.001–0.02). On average, for the seven years of each crop, the runoff

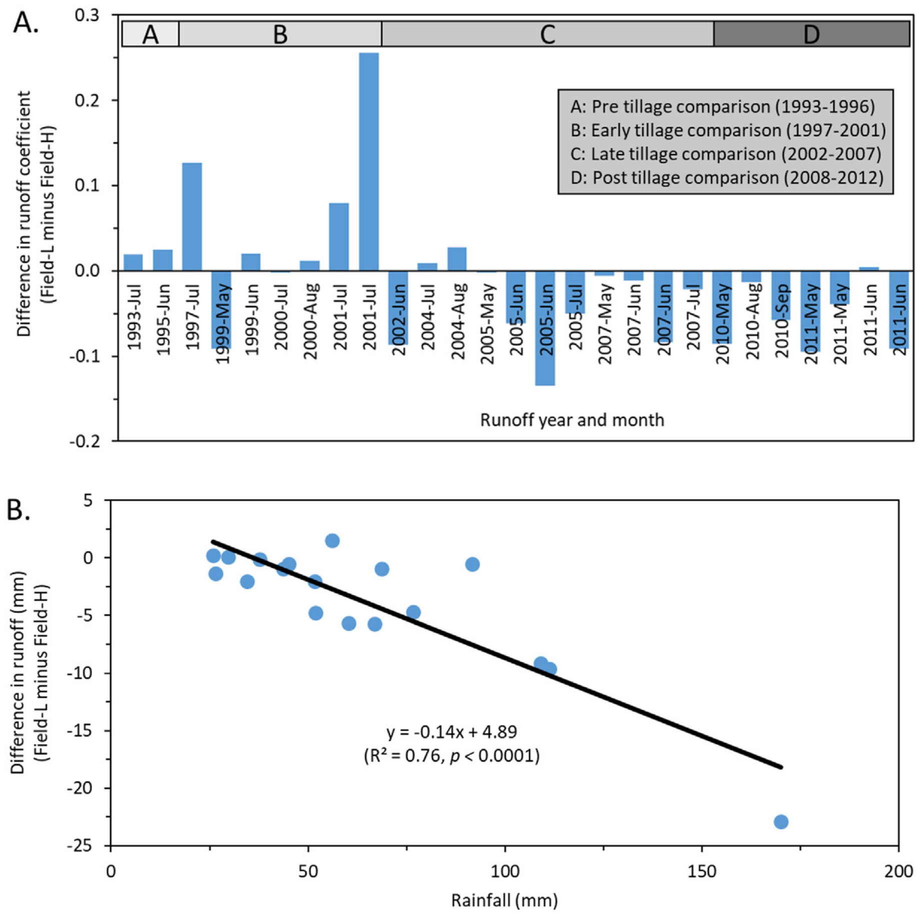

Fig. 4. Effect of tillage on rainfall runoff as demonstrated by (A) the differences in runoff coefficients between the two fields for events where monthly runoff occurred in at least one field (cases with no runoff from either field were excluded). The value of each bar is calculated as the runoff coefficient in the non-intensively tilled Field-L minus the coefficient in the intensively tilled Field-H. The whole study period is divided into pre, early, late and post tillage-comparison, respectively. (B) Relationship between the differences in runoff depths (Field-L minus Field-H) and depths of gross rainfall for the runoff events (with >0 mm runoff in at least one field) that occurred during the periods of late and post tillage-comparison (i.e., 2002–2012).

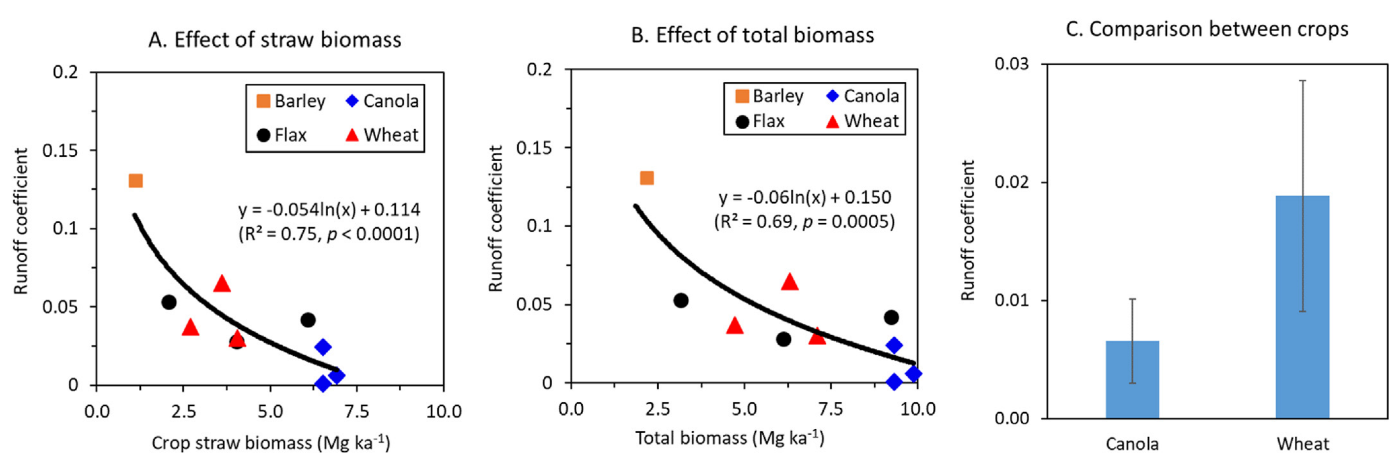

Fig. 5. Crop effects on rainfall runoff. (A) Relationship between growing-season level runoff coefficients and crop straw biomass in the intensively tilled Field-H for years with runoff >0 mm (n = 10). (B) The crop and runoff relationship developed using total biomass (n = 10). (C) Effect of crop type on growing-season level runoff coefficients in Field-H, where each bar represents the mean value of seven years including the years with zero runoff, and error bars are for standard errors (n = 7).

coefficients were 0.02 for wheat and 0.007 for canola (Fig. 5C). These suggest the potential to reduce runoff through crop management, by using crops that produce more biomass or increasing crop biomass production. A greater crop biomass increases water use by the crop and possibly also water infiltration [18], contributing to reduced runoff generation. Also, a greater coverage of crop reduces the impacts of raindrops on the soil surface and increases rain interception. Our inter-comparison study using annual crops complements well previous studies comparing perennial and annual crops [20–22].

3.3. Predicted runoff under changing rainfall patterns, cropping systems and tillage methods

Scenario analyses using the regression models developed in this study (Table 2) showed that changes in gross rainfall and production levels will affect runoff for both wheat and canola (Table 3). In general, increases in rainfall or decreases in crop biomass will likely increase runoff. The growing-season scenario showed that an increase in gross rainfall by 20 % (i.e., an increase of 65 mm from 325 mm – the average rainfall during

Table 3
Growing-season level changes in runoff under various scenarios of changing rainfall and crop production.

Tillage categories and models	Scenarios	Changes in runoff	
		Wheat	Canola
High intensity tillage Model: Runoff (mm) = 0.083*Rain (mm) – 2.71*total biomass (Mg ha^{-1}) – 0.69	• **Current average growing-season rain and production level (baseline)** [a]	**Baseline runoff 10 mm**	**Baseline runoff 1.9 mm**
	• Growing-season rain increase by 20 %	↑5.4 mm, 54 %	↑5.4 mm, 290 %
	• Growing-season rain decrease by 20 %	↓5.4 mm, 54 %	↓1.9 mm, 100 % (no runoff)
	• Crop production increase by 50 %	↓8.1 mm, 81 %	↓1.9 mm, 100 % (no runoff)
	• Crop production decrease by 20 %	↑3.3 mm, 32 %	↑4.9 mm, 260 %
	• Rain increase by 20 % and crop production increase by 50 %	↓2.7 mm, 27 %	↓1.9 mm, 100 % (no runoff)
	• Rain decrease by 20 % and crop production decrease by 20 %	↓2.1 mm, 21 %	↓0.5 mm, 27 %
Non-intensive tillage Model: Runoff (mm) = 0.046*Rain (mm) – 2.30*total biomass (Mg ha^{-1}) + 6.88	• **Current average growing-season rain and production level (baseline)** [a]	**Baseline runoff 8 mm**	**Baseline runoff 1.1 mm**
	• Growing-season rain increase by 20 %	↑3.0 mm, 37 %	↑3.0 mm, 270 %
	• Growing-season rain decrease by 20 %	↓3.0 mm, 37 %	↓1.1 mm, 100 % (no runoff)
	• Crop production increase by 50 %	↓6.9 mm, 86 %	↓1.1 mm, 100 % (no runoff)
	• Crop production decrease by 20 %	↑2.8 mm, 34 %	↑6.3 mm, 500 %
	• Rain increase by 20 % and crop production increase by 50 %	↓3.9 mm, 49 %	↓1.1 mm, 100 % (no runoff)
	• Rain decrease by 20 % and crop production decrease by 20 %	↓0.2 mm, 3 %	↑1.2 mm, 100 %

To simplify the comparisons between scenarios, the models with gross rain and total biomass were used for both high intensity tillage and non-intensive tillage groups.
[a] Average growing-season rain was 325 mm over the 20-year study period, and average total biomass production was 6 Mg ha^{-1} for wheat and 9 Mg ha^{-1} for canola.

1993–2012) may increase runoff by 5.4 mm in a high-intensity tillage system and 3.0 mm in a low-intensity tillage system (Table 3). However, an increase in rainfall may help increase crop production in the Canadian Prairies, which may in turn offset the increased runoff associated with rainfall increase.

It should be noted that runoff generation can be significantly affected by the rainfall amount delivered by a given event. Depending on how the 65 mm rainfall occurred in the scenario analyses, the increase of runoff could range from 0 mm in a scenario where all the rainfall occurred in many small events (<25 mm) to 47 mm in another scenario where the rainfall occurred on top of a 150 mm rainfall event (i.e., 215 mm rain in the event, Table 4). Despite this variation based on the sizes of rainfall events, the models developed (Table 2) are useful for predicting general responses of growing-season runoff to rainfall.

Under the current average rainfall conditions, a 50 % increase in crop biomass production could reduce runoff by 81%–86 % in wheat and 100 % in Canola (Table 3). This can be attributed to an increase in crop water use (including both rain interception and evapotranspiration). As wheat and canola had different amounts of average total biomass (wheat: 6 Mg ha^{-1}; canola: 9 Mg ha^{-1}), they had different baseline runoff depths. Their runoff responses to changing rainfall and biomass production levels were somewhat different. For example, following the 50 % biomass increase in the high-intensity tillage system, runoff from wheat was reduced from the baseline value of 10 mm–1.9 mm, but in canola from the baseline 1.9 mm to 0 (Table 3). If the same effort was needed to increase crop biomass by 50 % for both wheat and canola, doing this in wheat would have a greater benefit in runoff reduction. Yet, the efficiency of increasing crop biomass in reducing runoff changes with changing rainfall regimes. For example, when gross rainfall increased by 20 %, the runoff reduction potential decreased from 8.1 mm to 2.7 mm in the scenario of increasing 50 % wheat production in the high-intensity tillage system (Table 3).

Runoff potential can also be reduced by changing tillage from a high-intensity tillage system to no-till. However, the efficacy of changing tillage in runoff reduction varies with the size of the rainfall event. The tillage practice change was estimated to reduce runoff by only 2 mm for a 50 mm rainfall event but reaching 16 mm for a 150 mm rainfall event (Table 4). In addition, as the non-intensive tillage system had lower runoff potential than the high-intensity tillage system, in most cases the

Table 4
Event-level changes in rainfall runoff under various scenarios of changing gross rainfall and tillage.

Scenario categories	Specific scenarios	Models[b]	Predicted changes in runoff
Changing rainfall: An increase of growing-season rainfall by 20 % or 65 mm[a], which occurs as:	• many small events with rainfall <25 mm	Y = 0 (X ≤ 25; Model I)	No change
	• a single event with 65 mm rain	Y = 0.016X - 0.16 (X ≤ 105; Model II)	↑ 0.9 mm
	• added to an average rainfall event of 25 mm	Y = 0.016X - 0.16 (X ≤ 105; Model II)	↑ 1 mm
	• added to a big rainfall event of 150 mm	Y = 0.717X - 73.7 (X > 105; Model III)	↑ 47 mm
Changing tillage from high intensity tillage to no-till	• for a 50 mm rainfall event	Y = −0.14X + 4.89 (0 < X < 200; Model IV)	↓ 2 mm
	• for a 150 mm rainfall event	Y = −0.14X + 4.89 (0 < X < 200; Model IV)	↓ 16 mm

[a] The value of 65 mm was calculated as a 20 % increase of 325 mm, and the 325 mm was the average total rainfall from May–September for the years 1993–2012.
[b] Model I was based on the overall observations shown in Table 1 (Y: runoff in mm), Models II and III based on the piecewise regression in Fig. 2A (Y: runoff; X: rainfall; both in mm), and Model IV based on the linear regression in Fig. 3B (Y: change in runoff; X: rainfall; both in mm).

former had smaller changes in runoff as compared to the latter under the same changes in rain and crop production (Table 3).

In the Canadian Prairies, significant changes in rainfall patterns [10], crop production [25] and tillage [18] have taken place in the last 50 years. From the 1970s to the 2010s, for example, no-till has increased from 0 % [29] to 65 % [26]. Meanwhile, yields of wheat and canola have almost doubled and seeding areas of canola and corn have dramatically increased [25]. There has also been an increasing interest in growing corn and soybean in place of the traditional wheat-canola rotation [25]. These changes are anticipated to have considerably affected field and watershed hydrology. The changes are ongoing and will continue impacting runoff and water quality. It is important to assess regional water retention due to past and future changes in rainfall and management to better inform runoff mitigation measures. However, such an assessment is outside the scope of the present study.

4. Conclusions

Although most areas of the Canadian Prairies have generally small amounts of rainfall runoff, this study shows that rainfall-runoff processes can be significant in some years, especially during large (extreme) rainfall events. Runoff generation was affected by rainfall patterns, crop production (both crop type and biomass) and tillage methods. At the growing-season level, runoff significantly increased with increasing rainfall and decreasing crop biomass production. At the event-level, the rainfall-runoff relationship followed a piecewise regression model in which runoff increased slowly before reaching a rainfall "breakpoint" (105 mm gross rain in this study), rising sharply afterwards. Compared to high-intensity tillage, long-term conservation tillage showed promise to reduce runoff during large events through enhancing water infiltration. Due to a greater biomass, canola generated less runoff than wheat. Scenario analyses showed that increasing crop biomass by 50 % from the current production level of 6 Mg ha^{-1} for wheat and 9 Mg ha^{-1} for canola under the current average rainfall conditions could reduce runoff by 81–86 % in wheat and 100 % in canola. Rain interception by crop canopy was shown to affect effective rainfall. When such an effect is combined with the crop effects on evapotranspiration and water infiltration, their influences on runoff generation is significant. Given the significant changes in rainfall patterns, tillage and crop production that have taken place in this region (and will continue), further research should extend the findings of this study to assess regional water retention strategies that account for climate and soil-crop management options to help inform better mitigation measures for nutrient load reduction. It should be noted that the examination of crop biomass and its impacts on runoff both in this study and other studies in the Canadian Prairies [20–22] have been limited to the crop itself. In fact, there can be significant amounts of weed vegetation during the growing season of the crop and post harvest, and volunteer crop growth post harvest. Both the weeds and volunteer crop growth potentially affect runoff and nutrient export during snowmelt and rainfall, which should be further investigated.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Jian Liu: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **David A. Lobb:** Writing – review & editing, Funding acquisition, Conceptualization. **Jane A. Elliott:** Writing – review & editing, Funding acquisition. **Merrin L. Macrae:** Writing – review & editing, Funding acquisition. **Helen M. Baulch:** Writing – review & editing, Funding acquisition. **Diogo Costa:** Writing – review & editing.

Declaration of competing interest

The first author Jian Liu is affiliated with Climate Smart Agriculture, as an Editorial Board Member. He was not involved in the editorial review process or the decision to publish this article. All other authors declare that they have no competing interests related to this work.

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Appendix A. Supplementary data

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