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Water quality effects of cover crop, grazing and tillage implementation in a long-term no-till wheat system

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ABSTRACT

Agricultural anthropogenic nitrogen (N) and phosphorus (P) continue to be major surface and subsurface water pollutants in developed countries. Integrated crop-livestock systems in the semi-arid Texas Rolling Plains are characterized by continuously cultivated monoculture combined with grazing. Improperly managed grazing can increase soil compaction, and subsequently, decrease infiltration, which leaves the soil exposed to erosion. Grazing is therefore of paramount importance to water quality. Cover crop (CC) use improves soil ecosystem services and functions. The objective of the current study was to characterize soil water quality following CC under continuous wheat (*Triticum aestivum*), grazing, tillage, and no-till practices under a typic Haplustepts, Rotan clay loam soil type. Treatments evaluated include 1) conventional tillage without a CC (CT); 2) no-till without a CC (NT); 3) no-till with a CC (NTC); and 4) no-till with a grazed CC (NTCG). Portable rainfall simulators were used to assess surface runoff water quantity and quality after CC implementation in a long-term no-till continuous wheat system. Cover crop treatments, both grazed and un-grazed, reduced the amount of runoff by 4–6 times compared to no CC treatments (NT and CT). Converting 12-year-old NT to CT reduced infiltration by at least 43 % and increased runoff by 58 % compared to long-term NT. Consequently, total solids load and concentration for CT were 4–14 times greater than all NT treatments (NT, NTC, NTCG). Conventional tillage (CT) also increased total P loads and concentrations by 2–11-fold compared to all NT treatments ($p < 0.05$). Rainfall events occurring within three weeks after CC termination resulted in about 6 times greater soluble reactive P (SRP) (except NTCG) and about 2–3 times greater dissolved organic C (DOC) concentrations from CC treatments than non-CC treatments, although this was not observed for subsequent runoff events. Tilling the soil had more deleterious effects compared to flash grazing CC. Adopting NT, either alone, or long-term in combination with CC (either flash grazed or un-grazed) are potentially sustainable viable practices in semiarid regions that can reduce environmental contamination.

1. Introduction

Water quality impairment is a major issue in the US and worldwide. Within the US, agriculture is identified as the leading source of sediment, pathogens, and nutrients in rivers, and the second highest contributing source of impairment for lakes, ponds, and reservoirs. Based on the 2021 U.S. Environmental Protection Agency (USEPA) National Assessment Database, 52.9 % of the assessed river and stream miles in the U.S. were identified as impaired or not supporting one or more of their designated uses (USEPA, 2020). Furthermore, 70.9 % of the assessed lake, pond, and reservoir acres were identified as impaired or not supporting designated uses. Sediment, pathogens, and nutrients are top sources of impairment in the nation's waters. Whilst the importance of fertilizers cannot be overemphasized, agriculture anthropogenic nitrogen (N) and phosphorus (P) are major pollutants of both surface and subsurface water in the U.S. These nutrients are discharged into water bodies from farmlands through waterways and leach into surface and groundwater. Enriching water bodies with N and P

Abbreviations: RO, Runoff; I, Infiltration; TRO, time to runoff initiation; TS, total solids; TP, total phosphorus; SRP, Soluble reactive phosphorus; SOC, soil organic carbon; DOC, NH_4^+-N, dissolved organic carbonammonia-N; , NO_3^-–N, nitrate-N; N, Nitrogen; P, phosphorus; CT, conventional tillage; NT, no-tillage; NTC, no-tillage with the cover crop; NTCG, no-tillage with a grazed cover crop; CC, cover crop; mt, metric tonne; mg, milligram; ha, hectare; ICL, Integrated crop-livestock; Fig., Figure.

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(eutrophication) fosters algal bloom creating oxygen-depleted dead zones in surface waters (Sharpley, 1979; Diaz and Rosenberg, 2008; Scavia et al., 2017). Eutrophication inhibits water use for fisheries, recreation, industry, agriculture, and drinking (Carpenter et al., 1998), increasing greenhouse gasses release rates (Rosemond et al., 2015).

Introducing cover crops (CC) during the summer fallow period and adopting no-till in continuous wheat production systems is envisaged to improve soil ecosystem services and functions mitigating water pollution. Cover crops are grown to keep the soil covered, reduce soil erosion, surface runoff, and nutrient loss, add organic matter, and enhance soil's biological, chemical, and physical properties (Kaspar et al., 2011). Cover crop canopies and residues reduce raindrop impact on the soil surface, curtailing inter-rill erosion (Kaspar et al., 2011). Furthermore, they also create surface roughness that increases infiltration and reduces runoff initiation (Blanco-Canqui et al., 2013). Below-ground cover crop root biomass also enhances infiltration, reducing runoff and soil erosion (De Baets et al., 2011). Cover crops have been reported to reduce sediment loss, and consequently, P and N loss (Sharpley et al., 1991). Whilst CC significantly reduce quantities of dissolved nutrients transported into waterways through lowering runoff volumes, their capacity to reduce dissolved nutrients in the runoff can vary (Blanco-Canqui et al., 2018). Cover crop senescence concentrates P in above-ground herbage, thereby increasing dissolved P in runoff (Sharpley, 1981; White and Weil, 2011; Liu et al., 2014).

Integrated crop-livestock (ICL) systems that combine wheat (*Triticum aestivum*) production and grazing are common in the US southern and central great plains semi-arid regions. These dual-purpose monoculture wheat systems are often practiced under conventional tillage with grazing. Grazing can increase soil compaction, decrease infiltration, and increase the potential of soil erosion, thus escalating the potential for increased runoff volumes sediment loss, and dissolved nutrients churned into the environment, which in turn can diminish both water quality and soil fertility (Sulc and Tracy, 2007; Van Haveren, 1983; Daniel and Phillips, 2000; Daniel et al., 2002; Wheeler et al., 2002). Wood and Wood (1988) reported sediment load doubled under grazing of rangeland systems. In another study, grazing livestock increased concentrations of total solids (by 52 %), total organic carbon (11 %), chemical oxygen demand (7 %), ammonia–N (6 %), nitrate–N (45 %), total P (37 %), and soluble P (48 %), whilst Total Kjeldahl Nitrogen decreased by 19 % compared to the grazed area when no livestock was present (Schepers and Francis, 1982). Whilst numerous research (Faust et al., 2020; Park et al., 2017; Wilson et al., 2014; Roche et al., 2013; DeLaune and Sij, 2012; Wood and Wood, 1988; Schepers and Francis, 1982) have been done on grazing and water quality not much has focused on grazing summer CC and its subsequent impact on water quality. Grazing is an important component of ICL systems common in semi-arid ecoregions. Grazing CC offers the opportunity to alleviate CC production costs (Franzluebbers and Stuedemann, 2007). There is a paucity of information on the impact of grazing CC on water quality. Therefore, the objective of this study was to evaluate the impact of grazing CC and tillage, on water quality under continuous wheat production on the potential to mitigate pollution and associated eutrophication. We hypothesized that CC (grazed or un-grazed) under NT practice during fallow periods would improve soil physical properties, and ultimately, water quality churned into the environment.

2. Methods and material

2.1. Study site and experiment design

The entire study site was under rainfed NT wheat (*Triticum aestivum*) production since 2001 and is located at the Texas A&M AgriLife Research, Smith Walker Research Unit (34° 03'28.7 "N 99° 14'35.8 "W) near Vernon, Texas. The soil type is a typic Haplustepts, Rotan clay loam (Fine, mixed, superactive, thermic Pachic Paleustolls), with a particle size distribution of 21.5 % sand, 39.1 % silt, and 39.4 % clay. The average annual precipitation is 711 mm and mean annual temperature of 17.1 °C (US climate data, 2017).

The experimental design was initiated in the summer of 2013 as a randomized complete block design with four treatments replicated four times with a research plot size of 2000 m^2 each on relatively flat ground, $<$ 2 % slope. Summer cover crops were grown on the same plots each year during the fallow period, while wheat was seeded in the winter. After the third year of cover crop implementation, water quality was assessed for the following treatments: 1) CT wheat without a cover crop (CT); 2) NT wheat without a cover crop (NT); 3) NT wheat with a terminated summer cover crop (NTC); 4) NT wheat with a grazed summer cover crop (NTCG). Conventional till plots were established in spring 2013 in a field that had been under NT since 2001 using a plow disc and chisel sweep to a depth of 15 cm. This tillage was repeated for CT plots every season of the current study. Fertilizer applications were applied only to winter wheat every fall and spring. Soil samples were collected preceding rainfall simulation on the plots and was done using a 1.8 cm diameter soil probe at 0–5 and 5–15 cm depths from twenty randomly distributed spots in each plot to make composite samples. Soil nutrients were analyzed using standard methods. Inorganic N, NO_3^-N, and NH_4^+–N, was determined by extracting 2 g of soil with 1 N KCl at a 10:1 extractant to soil ratio using colorimetric methods after filtering through the Whatman number 42 filter paper. Nitrate-N (NO_3^-–N) was analyzed following Cd reduction as summarized by Keeney and Nelson (1982), while NH_4^+–N was determined as described by Dorich and Nelson (1983). A Skalar San-plus Analyzer (Skalar Analytical B.V., North Brabant, Netherlands) was used for NO_3^-–N and NH_4^+–N analysis. Soil total N (TN) and organic C (SOC) were analyzed using a Macro Elementar analyzer (Vario Max CN, Elementar Analysensysteme GmbH, Langenselbold, Germany) as described by McGeehan and Naylor (1988) after drying and grinding. Phosphorus (P) analysis was conducted using Inductively coupled plasma (ICP) (Varian Vista-MPX axial flow ICP, Varian Inc., Palo Alto, California, USA) after extracting with Mehlich solution as described by Mehlich (1984). Soil nutrient levels in fall 2015 prior to rainfall simulation are presented in Table 1. Antecedent soil moisture was quantified using the gravimetric method to a depth of 15 cm.

2.2. Cover crop management

A warm season multi-species cover crop mix consisting of grasses and legumes was planted each summer after wheat harvest for three consecutive years. Generally, the mix with individual rates in parenthesis [@ kg ha^{-1}] was composed of; Iron & Clay Cowpea (*Vigna unguiculata*) [@ 5.6], Guar (*Cyamopsis tetragonoloba*) [@ 6.7], Mungbeans (*Vigna radiate*) [@ 6.7], Pearl Millet (*Pennisetum glaucum*) [@ 2.2], Giant Foxtail Millet (*Setaria italic*) [@ 1.1], Forage Sorghum [*Sorghum bicolor* (L.) Moench.] [@ 3.4], and Buckwheat (*Fagopyrum esculentum*) [@ 2.2]. The third year produced biomass ranging from 2381 to 3120 kg ha^{-1}. Full details of the cover crop mixture and management are provided in Mubvumba et al., 2021. All CC, both grazed and un-grazed were terminated using glyphosate and/or paraquat in August/September every year. Grazing paddocks, 4000 m^2 in size, were established before grazing by fencing adjacent grazed cover crop treatment plots. The paddocks were flash grazed each year for 6–24 h (Mubvumba et al., 2021). In 2015, 31 available cattle (18 cows and 13 calves) with an estimated live cattle weight of 11,340 kg were rotated through the four paddocks, six hours per paddock, from the 9th to the 10th of September. Flash grazing is grazing a small area in a short time using a large concentration of animals (Rocky, 2011). Mubvumba et al. (2021) reported that cover crop biomass for NTCG was 3133 kg ha^{-1} pre-graze and 1391 kg ha^{-1} post-graze.

2.3. Rainfall simulation

Portable rainfall simulators were used for assessing runoff water

Table 1
Soil water and nutrient levels in fall 2015.

Treatment	Soil water (%) and nutrient (mg kg^{-1}) levels at 0–5 and 5–15 cm depth										
	NO_3^- - N		NH_4^+ - N		Total N		Mehlich III P		SOC		SWC (%)
Depth(cm):	0–5	5–15	0–5	5–15	0–5	5–15	0–5	5–15	0–5	5–15	0–15
CT	24.3a	23.5a	11.2a	6.3a	767b	550a	27.8b	12.5a	6967a	6351a	4.2b
NT	14.5b	8.8b	9.7a	5.1a	867ab	300b	50.8a	10.5a	7667a	5467a	5.2a
NTC	5.0c	1.5c	14.2a	4.9a	832ab	367b	35.8b	8.0a	7733a	5767a	5.3a
NTCG	3.0c	2.0c	14.6a	8.0a	933a	367b	38.8b	11.3a	7711a	5611a	3.5b

†Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).
CT, conventional-till; NT, no-till; C, cover crop; G, graze. Nitrate-N (NO_3^- - N), Ammonia-N (NH_4^+ - N), Phosphorus (P); SOC, soil organic carbon; SWC, soil water content.

quantity and quality from the treatment plots as described by DeLaune and Sij (2012). Two rainfall simulation events on each plot were conducted on October 7th and October 27th, 2015, which were 22 and 42 days after cover crop termination. Runoff plots (micro-plots) (1.5 m x 2.0 m) were constructed within plots for each treatment (Fig. 1). Rainfall simulators provided a typical 7 cm hr^{-1} storm event during the experiment (Fig. 1). Upon the initiation of runoff, the rainfall simulation process continued for an additional 30 min. Runoff water was collected during this time in a single 114-liter collection barrel using electric pumps (Fig. 1). Time to runoff and runoff volumes were recorded and infiltration rates were calculated. Infiltration was calculated as the total amount of water applied per plot minus runoff volume collected. Runoff weight was continuously recorded over time every 5 min and associated grab water samples were simultaneously collected. Aliquots were acidified with sulfuric acid (H_2SO_4) after filtering through a 0.45 µm membrane filter for analysis of nitrate-N (NO_3^-–N), ammonia-N (NH_4^+–N), and soluble reactive P using a segmented flow analyzer. These analyses were as outlined by APHA (2005) for NO_3^-–N and soluble reactive P and USEPA (1983) for NH_4^+–N. Total P was determined by a segmented flow analyzer according to the ascorbic acid reduction method (APHA, 2005), following digestion with nitric acid. Total solids (TS) were determined by oven drying a 20 ml aliquot at 105 °C for 24 h (APHA, 2005). Dissolved organic carbon (DOC) was determined on non-acidified samples using high-temperature combustion according to APHA method 5310 (APHA, 2005).

2.4. Statistical analysis

The collected data were analyzed using Proc GLIMMIX using SAS Version 9.4 (SAS Institute Inc., Cary, NC). The GLIMMIX procedure combines the characteristics of generalized linear models and mixed models (SAS Institute, 2017). Treatment was considered a fixed effect and block random. Mean separations were determined using Fisher's protected least significant difference (LSD) at $P < 0.05$ when the ANOVA was significant at $P < 0.05$.

3. Results and discussion

3.1. Antecedent soil water and nutrient levels

Prior to the first rainfall simulation event, the concentration of soil P was highest under long-term NT due to surface stratification (Daryanto et al., 2017) and smallest under CT in the surface soil due to redistribution through plowing (Selles et al., 2002) (Table 1). Converting the long-term NT to continuous tillage (CT) spiked the mineralization of organic N to inorganic NO_3^- - N through decomposition hence the higher NO_3^- - N concentration in CT than NT that was observed (Spiess et al., 2020). Cover crops (NTC and NTCG) recorded the lowest NO_3^- - N due to immobilization of NO_3^- - N by the high C/N ratio biomass that was produced during the 3-year study period (Data not reported). The high soil mehlich III P under NT that was observed in the surface soil layer

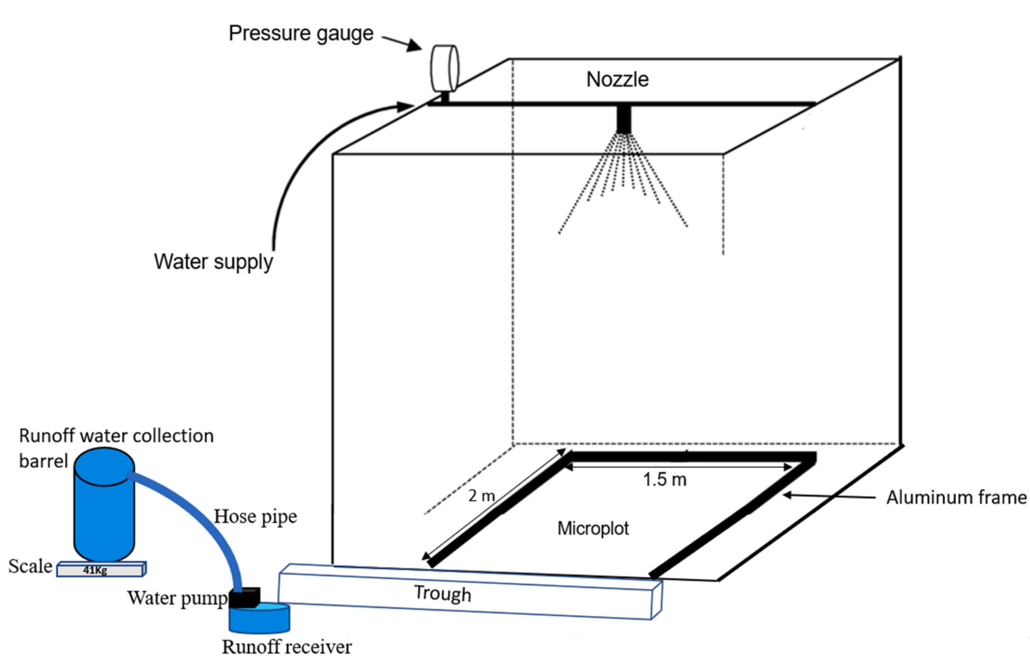

Fig. 1. Rainfall simulator frame. Encircled with tarps during raining except for the front to control drift. The top of the trough is covered with a piece of lumber to prevent rain from directly falling into the trough. Both the trough and runoff receiver are put below ground. The water pump continuously pumps runoff into the barrel. Changes in runoff weights are periodically recorded as displayed on the scale.

can potentially increase the amount of dissolved reactive P in runoff water, although increased infiltration under NT may curtail the amount of runoff, and thus mitigate amounts of dissolved reactive P discharged into the environment (Daryanto et al., 2017). The NT and NTC treatments had the highest recorded soil water content compared to CT and NTCG just before the first rain simulation event (Table 1). No significant differences in NH^4+ - N, and SOC were observed amongst all treatments (Table 1).

Agronomically, CT had sufficient inorganic nitrogen (NO_3^- - N + NH_4^+ - N) in the top two soil layers based on Texas A&M AgriLife Extension soil fertility recommendations pegged at 30 mg kg^{-1}inorganic nitrogen in this ecoregion for wheat under grazing and grain production for yield expectations ranging 1.3–2.0 mt/ha. Cover crop treatments (NTC and NTCG) had the least inorganic nitrogen, about half the recommended concentration in the soil surface layer of 0–15 cm. However, there were no statistical differences in TN amongst all treatments, with CT trending lowest. The higher TN for CT in the 5–15 cm depth ($p < 0.05$) can be attributed to leaching from the 0–5 cm depth (Hafif, 2014). All reported treatments' phosphorus concentrations were higher than the optimum P recommendation of 15 mg kg^{-1}.

3.2. Water quantity

Continuous tillage (CT) expedited the time to runoff initiation both in the first and second rainfall simulations compared to all other treatments ($p < 0.05$; Table 2). Only 1.5 mm of precipitation was received on the 24th of October, between the two rainfall simulation dates. All NT treatments: fallow, cover cropped; un-grazed and grazed (NT, NTC, and NTCG) did not significantly differ in time to runoff initiation in the first rainfall simulation event but in the second (Table 2). Comparable findings have been reported elsewhere, with Blanco-Canqui et al. (2013) reporting no significant differences in TRO between NT fallow using spring triticale and spring pea, although winter triticale significantly increased TRO three-fold. The shortest time to runoff that was observed under CT can be attributed to the associated lowest infiltration recorded for CT ($p < 0.05$; Table 2), caused by having the highest bulk density and reduced porosity for CT that was reported (Mubvumba et al., 2022).

Cover crops un-grazed or grazed (NTC and NTCG) significantly reduced runoff volumes in comparison to NT fallow and traditional CT practice ($p < 0.05$; Table 2; Fig. 2). While there was no significant difference for RO between NT and CT, infiltration rates were significantly greater for NT than CT during the first event. This can be explained by the fact that 76 % more rainfall was applied to NT compared to CT due to the significantly lower duration of runoff initiation for CT. Infiltration did not differ among NT treatments and all NT treatments resulted in significantly greater infiltration than CT by 69–86 %. As infiltration rates were not different among NT treatments, differences in runoff volume may be partly explained by a potential shift to saturated-excess flow for NT. Cumulative runoff was lowest for cover crop treatments (NTC and NTCG) for both rainfall simulation events ($p < 0.05$; Fig. 2). On average, cover crops reduced runoff volume by up to 60 % compared to CT. Similarly, related studies have reported runoff reductions ranging from 13 % to 78 % (Blanco-Canqui et al., 2015). The effect of cover crops

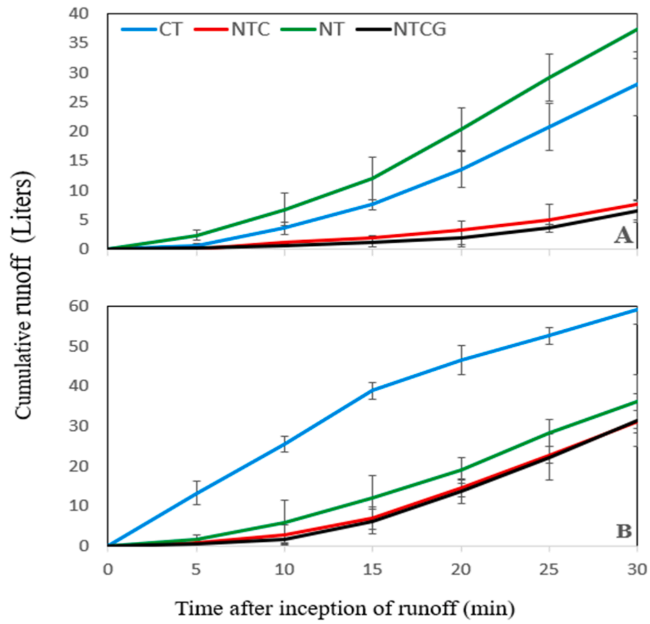

Fig. 2. Cumulative runoff. First event-October 7th, 2015 (A). Second event-October 27th, 2015 (B). CT, conventional-till; NT, no-till; C, cover crop; G, graze; min, minutes.

on reducing surface runoff is ascribed to improved soil properties and surface roughness due to CC growth and residue addition to the soil system (Mubvumba et al., 2022; Blanco-Canqui et al., 2013). Surface residues reduce runoff speed, allowing more soil-water contact time for water infiltration into the ground. Cover crops improved soil structure and aggregate stability through macropore formation, hence the observed increase in infiltration rates (Mubvumba et al., 2022; Arvidsson, 1998; Lipiec and Stepniewski, 1995).

The second rainfall simulation event revealed how catastrophic subsequent rain events can be under continuous tillage (CT) practice compared to conservation practices (NT, NTC, and NTCG). Conventional tillage generated the greatest amount of runoff among treatments, although the total rainfall applied was lowest for CT among all treatments ($p < 0.05$; Table 2). Infiltration was also significantly lowest for CT among all treatments. Other studies have shown up to an 80 % decrease in runoff loss using single species rye cover crop and eliminating tillage (Krutz et al., 2009; Kaspar et al., 2001). Tilling the site for three consecutive years after 12 years of NT practice resulted in CT reducing infiltration by 38 % and, increasing runoff by 72 % compared to NT with or without cover crops. DeLaune and Sij (2012) reported a 38 % increase in runoff due to the conversion of NT to CT. Subjecting the soil to tillage after 12 years of NT destroyed soil aggregates, compacting the soil and, increasing bulk density, which resulted in surface soil sealing and reduced infiltration rates (Mubvumba et al., 2022; Elliott et al., 1987).

Smith et al. (1987) also reported that NT and cover crops reduced

Table 2
Time to runoff initiation (TRO), infiltration, and runoff volumes (RO) as affected by treatments.

Treatment	Intensity cm hr^{-1}	October 6, 2015				October 27, 2015			
		TRO (min)	Rainfall (cm)	RO (cm)	Infiltration (cm)	TRO (min)	Rainfall (cm)	RO (cm)	Infiltration (cm)
CT	7	8.6b†	4.5b	0.94a	3.6b	2.9c	3.8c	1.9a	2.0b
NT	7	38a	7.9a	1.25a	6.7a	10.6a	4.7a	1.2b	3.5a
NTCG	7	24a	6.3a	0.22b	6.1a	4.9bc	4.1b	1.1b	3.0a
NTC	7	28a	6.7a	0.26b	6.5a	6.4b	4.2b	1.0b	3.2a

†Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).
CT, conventional-till; NT, no-till; C, cover crop; G, graze; min, minutes; cm, centimeters.

surface runoff and increased infiltration and stored soil water. Rasnake and Hargrove (1991) found that using winter wheat as a cover crop did not reduce runoff and TSS compared to NT with soybean residue, although it did in comparison with CT. Rainfall simulations did not show any differences in water infiltration rates due to cover crops or grazing in no-till systems. DeLaune et al. (2013), however, reported an increase in runoff by 1.5-fold and a decrease in infiltration by 1.3-fold under grazed out compared to the graze/grain system, which was a longer duration grazing than the flash grazing observed in our study. Flash grazing under the conditions in this study did not result in adverse runoff or infiltration rates.

3.3. Water quality

3.3.1. Nutrient and sediment loads

Conventional till had the highest concentrations and loads of total solids (TS) and total P (TP) in runoff for both the first and second days of rain simulations ($p < 0.05$; Table 3). The sediment load and concentration for CT were on average about 5–14 and 4–6 times greater than that for NT treatments for the first and second rain events, respectively. Total P load and concentration were both about 2–4 and 4–11 times greater than NT treatments for the first and second events, respectively ($p < 0.05$; Table 3). Conventional tillage leaves the soil susceptible to erosion, and thus more sediment loss. Since P adheres to soil particles and is carried along with solids, this explains the relationship between TS and TP runoff loads observed. DeLaune and Sij (2012) showed that converting no-till to conventional tillage increased runoff volumes by 38 % and that conventional tillage had 2.8 times higher TS and TP compared to no-till. Soluble reactive phosphorus (SRP) load and concentration were highest under NTC compared to all other treatments on the first date of rain simulation ($p < 0.05$; Table 3). Similarly, Sharpley et al. (1991) noted an increase in soluble P with cover crops. Grabber and Jokela (2013) showed a winter rye cover crop more than doubled total reactive phosphorus compared to NT with no cover. Phosphorus released from cover crop residue decomposition explains the highest NTC SRP values (Noack et al., 2012; Damon et al., 2014). The lower SRP concentrations and loads observed under NTCG compared to NTC are explained by reduced biomass due to cover crop grazing.

DeLaune et al. (2013) reported higher TP and SRP under graze-out compared to graze and grain systems. Research has shown variable impacts of cover crops on soil P ranging from no discernible effect (Eckert, 1991) to lowering soil P concentration (Hargrove, 1986). Generally, untilled systems tend to be higher in SRP whilst tilled soil has higher sediment-bound P (Karayel and Sarauskis, 2019; Zhang et al., 2015). The higher SRP associated with untilled soils is due to soil P surface stratification, which is characteristic of long-term no-till systems (Daryanto et al., 2017), whilst sediment-bound P common with tilled soils is due to adsorption of P to soil particle surfaces.

Results from the first date of rain simulation showed higher NH_4^+–N runoff concentrations and loads in treatments without cover crops compared to cover crop treatments, concurring with the findings of Siller et al. (2016), who showed mono-crop corn with higher NH_4^+–N runoff concentrations and loads in comparison to using rye, clover, or a combination thereof as cover. However, Smith et al. (2017) reported higher NH_4^+–N runoff loads and concentrations under cover crops compared to no cover treatments. The higher NH_4^+–N loads might be explained by NH_4^+ chemistry which, like P, is fixed by clay and is susceptible to erosion (DeLaune and Sij, 2012). Whilst we did not find any significant effect on nitrate-N concentration due to cover cropping, other studies noted decreased nitrate-N (Blanco-Canqui et al., 2013; Nyakatawa et al., 2006; Zhu et al., 1989). Blanco-Canqui et al. (2014) attributed the inability to effectively alleviate nitrate leaching under coarse-textured soils to low biomass quantity (< 1 Mg ha^{-1}). We did not find any effect due to grazing in this portion of the study. Cover crops have been reported to reduce nutrient loads downstream, alleviating pollution (Kovar et al., 2011). Several studies have reported cover crops' reduction of sediment load (Siller et al., 2016; Blanco-Canqui et al., 2013; Espejo-Pérez et al., 2013; Laloy and Bielders, 2010), with some showing associated TP and soluble phosphorus decreases (Siller et al., 2016; Blanco-Canqui et al., 2013; Kovar et al., 2011), however, Smith et al. (2017) showed cover crops' inability to reduce SRP runoff both loads and concentrations in agriculture fields.

The first date of simulated rainfall showed cover crop treatments NTCG and NTC exhibiting higher concentrations and loads of DOC compared to no cover crops treatments ($p < 0.05$; Table 3), with the NTCG treatment having the highest DOC compared to all treatments.

Royer et al. (2007) showed how incorporating corn residues increased DOC concentrations 6–17 times in surface RO. This was credited to soluble organic matter that was released due to residue microbial decomposition.

3.3.2. Nutrient concentration within runoff event

Discrete sediment and nutrient concentrations in runoff from the two rain simulation events are shown in Fig. 3 & 4. The routine and traditional conventional tillage (CT) practice increased sediment load constantly during the entire 30-minute raining period compared to

Table 3
Runoff loads and concentrations of total solids (TS), total phosphorus (TP), soluble reactive phosphorus (SRP), dissolved organic carbon (DOC), NO_3^+–N, and NH_4^+–N.

Treatments	Runoff Load											
	October 6, 2015						October 27, 2015					
	TS (kg ha^{-1})	**TP** (g ha^{-1})	**SRP** (g ha^{-1})	**DOC** (g ha^{-1})	**NO_3–N** (g ha^{-1})	**NH_{4+}–N** (g ha^{-1})	**TS** (kg ha^{-1})	**TP** (g ha^{-1})	**SRP** (g ha^{-1})	**DOC** (g ha^{-1})	**NO_3–N** (g ha^{-1})	**NH_{4+}–N** (g ha^{-1})
CT	484a†	95a	6b	456c	34a	34a	238a	59a	8ab	553a	50a	33a
NT	34b	22b	15b	645c	38a	39a	37b	5b	7b	890a	41a	17a
NTCG	91b	44b	17b	1485a	39a	12b	67b	9b	9ab	890a	35a	25a
NTC	55b	41b	40a	1157b	36a	20b	53b	13b	13a	891a	38a	32a
	Runoff Concentration											
	October 6, 2015						October 27, 2015					
	TS (mg L^{-1})	**TP** (mg L^{-1})	**SRP** (mg L^{-1})	**DOC** (mg L^{-1})	**NO_3^-–N** (mg L^{-1})	**NH_4^+–N** (mg L^{-1})	**TS** (mg L^{-1})	**TP** (mg L^{-1})	**SRP** (mg L^{-1})	**DOC** (mg L^{-1})	**NO_3^-–N** (mg L^{-1})	**NH_4^+–N** (mg L^{-1})
CT	6200a	1.22a	0.07b	5.8c	0.43a	0.43a	3053a	0.76a	0.10ab	7.1a	1.01a	0.42a
NT	433b	0.29b	0.20b	8.3c	0.49a	0.50a	477b	0.07b	0.09b	11.4a	0.52a	0.22a
NTCG	1167b	0.56b	0.26b	19.0a	0.50a	0.16b	660b	0.12b	0.12ab	11.4a	0.44a	0.33a
NTC	700b	0.52b	0.51a	14.8b	0.46a	0.26b	677b	0.17b	0.17a	11.4a	0.49a	0.41a

†Means within a column followed by the same letter are not different by Fisher's protected LSD (0.05).
CT, conventional-till; NT, no-till; C, cover crop; G, graze.

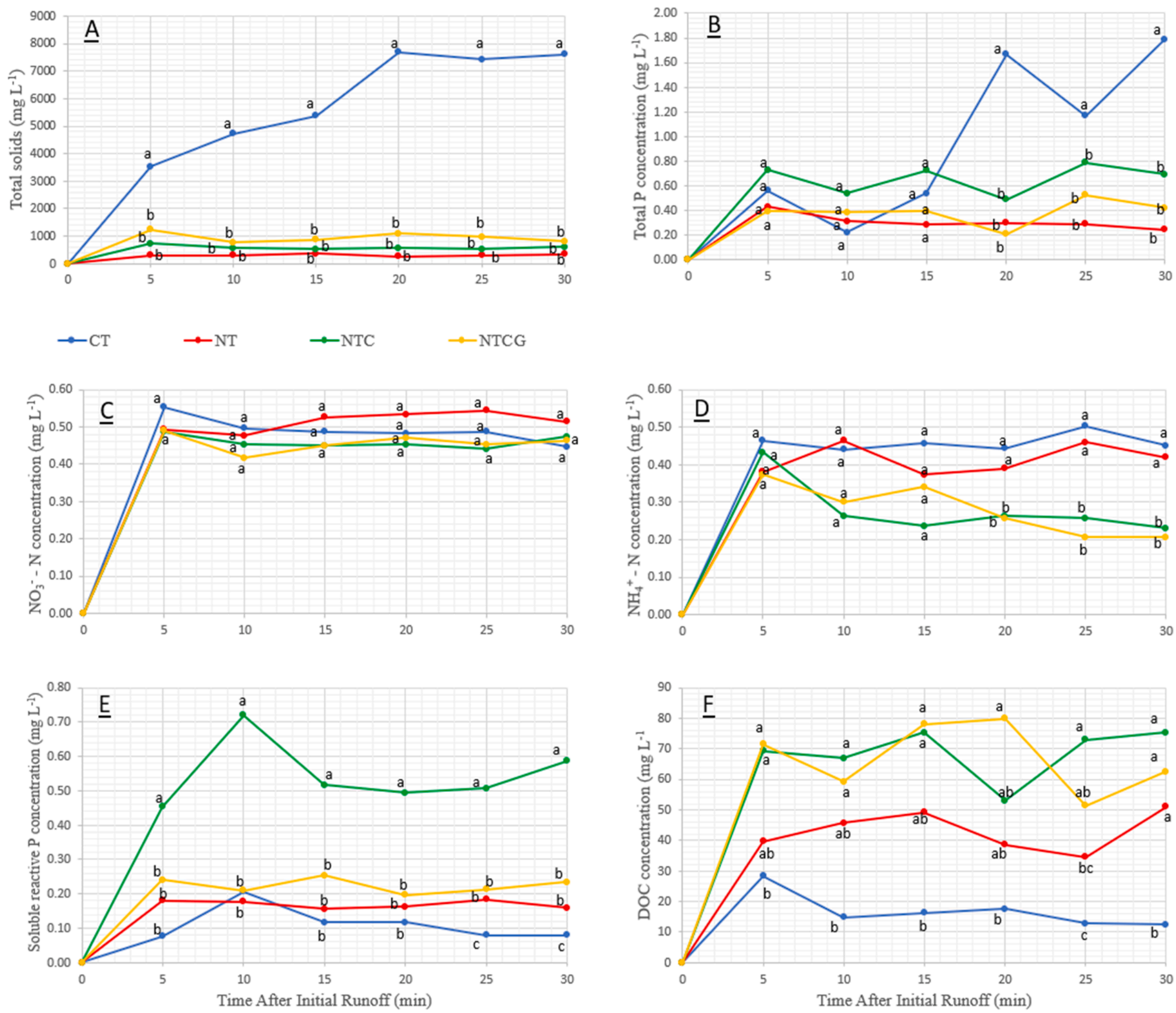

Fig. 3. First runoff event temporal trends. Points within each time after initial runoff labeled by the same letter are not different by Fisher's protected LSD (0.05). CT, conventional-till; NT, no-till; C, cover crop; G, graze. Discrete runoff concentrations for A: Total solids; B: Total P; C: NO_3^- - N; D: NH_4^+-N; E: Soluble reactive P and F: Dissolved organic carbon (DOC).

conservation practices (NT, NTC, and NTCG) in the first runoff event (Fig. 3a). Tillage disintegrates soil structure into vulnerable particles that are easily washed away suspended or dissolved in the runoff. Sediment concentrations in CT were up to 7-fold higher compared to conservation practices ($p < 0.05$). Comparable trends were observed in the second rain event, although with reduced sediment loads and a higher correlation between TS and TP (R^2 =0.89, p = <0.0001: Fig. 4A & 4B versus R^2 =0.56, p = <0.0001: Fig. 3A & B). The corresponding temporal variation observed between TS and TP can be attributed to the P chemistry adhesive characteristics to clay particles, hence eroded along with sediments in runoff water (Ezzati et al., 2020; DeLaune and Sij, 2012).

Cover crops (NTC) increased soluble reactive phosphorus that was channeled into the environment while grazing cover crops (NTCG) reduced above-ground biomass, consequently significantly lowering SRP that was conveyed into the natural environment in the first raining event (Fig. 3E). The NTC treatment SRP concentrations were at least double to triple those in the NT, NTCG, and CT treatments, respectively, during the entire runoff period ($p < 0.05$; Fig. 3E). The highest SRP observed under NTC can be explained by the cover crop-residue derived P that was added to the soil system upon cover crop termination. Phosphorus is released into the soil through decomposition and mineralization of cover crop residues (Noack et al., 2012; Damon et al., 2014). Grazing under the NTCG treatment reduced biomass by up to 67 %, possibly curtailing SRP concentrations in comparison to the NTC treatment. Similarly, cover crops have been reported to increase SRP elsewhere (Siller et al., 2016; Kovar et al., 2011). Contrary to our findings, some research showed NT without cover crops increased SRP due to surface stratification (Daryanto et al., 2017). Although our antecedent NT (without CC) soil data showed surface P stratification ($p < 0.05$; Table 1) the reason it was not reflected in SRP was possibly the increased infiltration that was detected under NT that reduced SRP that was transported into the environment (Daryanto et al., 2017). There were no significant differences in infiltration between fallow NT and NT with cover crops, un-grazed (NTC), or grazed (NTCG). The second rain event did not show any statistical differences in SRP amongst all treatments.

Continuous conventional tillage (CT) and leaving the land fallow (NT) initially spiked NO_3^- - N in runoff in comparison to cover cropped treatment plots (NTC and NTCG), reaffirming the use of cover crops in conserving soil nitrogen in the second runoff event (Fig. 4C). The non-CC practice (CT and NT) exhibited a 2-fold difference compared to cover crop treatments ($p < 0.05$; Fig. 4C). At the end of the runoff event, tillage (CT) had exhausted NO_3^- - N reserves showing the lowest NO_3^- - N concentrations compared to the rest of the treatments ($p < 0.05$, Fig. 4C). The lowest NO_3^- - N concentration initially observed under cover crop treatments compared to no cover treatments can be

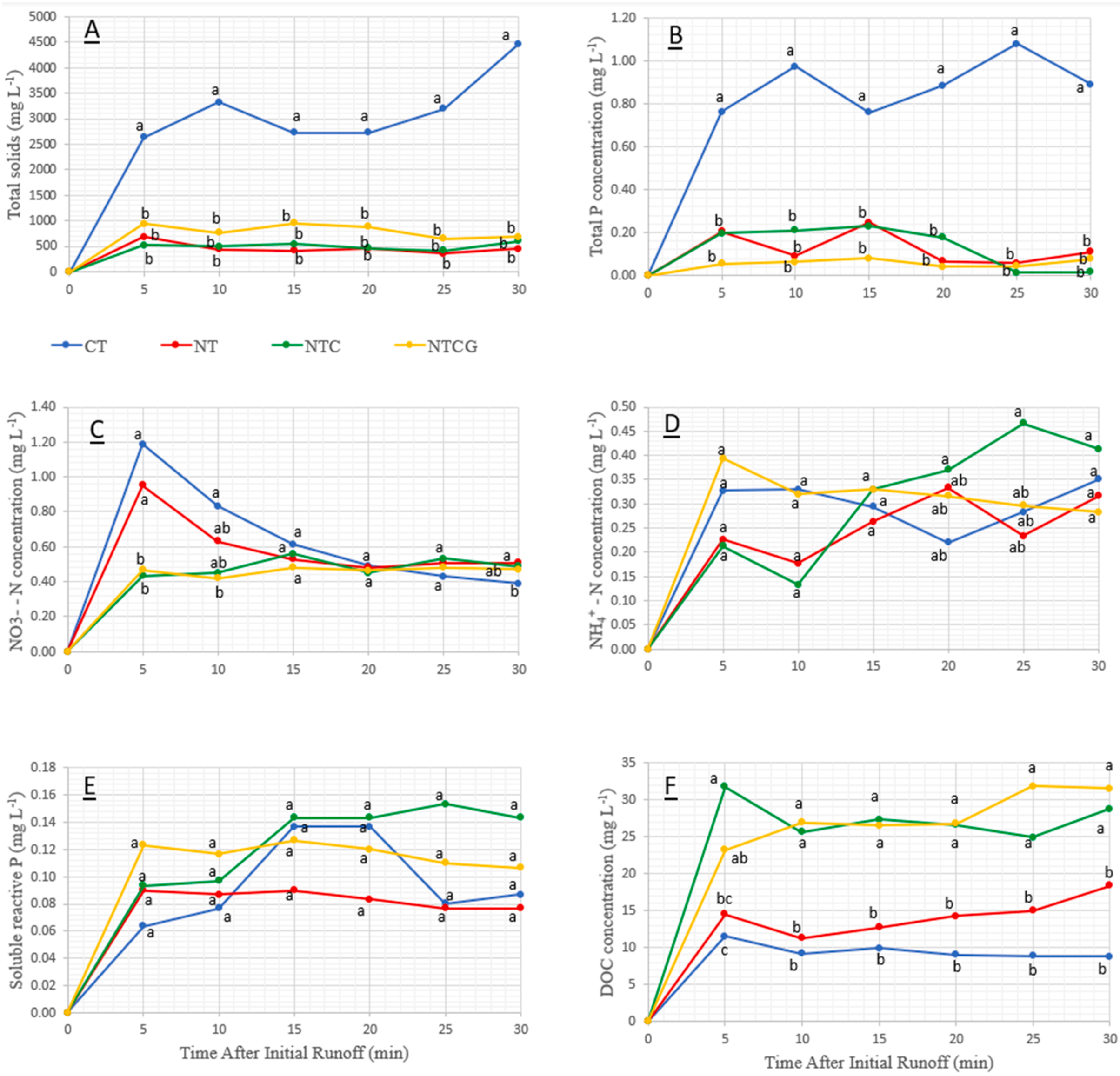

Fig. 4. Second runoff event temporal trends. Points within each time after initial runoff labeled by the same letter are not different by Fisher's protected LSD (0.05). CT, conventional-till; NT, no-till; C, cover crop; G, graze. Discrete runoff concentrations for A: Total solids; B: Total P; C: NO_3^- - N; D: NH_4^+-N; E: Soluble reactive P and F: Dissolved organic carbon (DOC).

attributed to cover crops scavenging available inorganic N during their growth cycle (Dabney et al., 2010; Quemada et al., 2013; Blanco-Canqui et al., 2015), whilst higher NO_3^- - N concentrations under NT cover crops at the end of the runoff event is due to their ability to sequester N in particulate organic matter (Al-Sheikh et al., 2005; Cambardella and Elliott, 1992; Havlin et al., 1990), conserving N that can later be available for plant use (Delgado, 2010). The decrease in NO_3^- - N observed under cover crop treatment in this investigation concurs with other findings (Blanco-Canqui et al., 2013; Nyakatawa et al., 2006; Zhu et al., 1989).

Ammonia – N discrete runoff samples did not show any significant differences in the second event but did in the first one. The no cover crop treatments (CT and NT) had double the NH_4^+ - N concentrations compared to the cover crop treatments (NTC and NTCG) at the 20-, 25-, and 30-minute sampling points during the runoff event ($p < 0.05$, Fig. 3D). This was consistent with what Siller et al. (2016) reported. However, Smith et al. (2017) showed cover crops increasing NH_4^+-N concentrations with varying P fertilizer inputs. The lower NH_4^+ - N concentrations detected under NTC and NTCG in this study could be due to the high C/N ratios (up to 48) observed in cover crop residues (Data not reported), which resulted in the immobilization of NH_4^+ - N.

Dissolved organic carbon (DOC) concentrations in discrete runoff samples exhibited similar patterns under both runoff events. The first event showed DOC being discharged into the environment decreasing in the order NTC&NTCG>NT>CT. The NTC and NTCG treatments churned 2.5 times the CT DOC concentration at 5 min after runoff inception, rising to about 6-fold CT compared to NTC, at the end of the event ($p < 0.05$; Fig. 3F). The cover crop treatments (NTC and NTCG) trended highest in all discrete samples under both runoff events compared to CT and NT and was more pronounced in the second runoff event ($p < 0.05$; Fig. 3 & 4). Cover crops have been reported to increase DOC concentrations (Olson et al., 2014), with the potential of it being discharged into the environment, as was exhibited in this investigation. This DOC is ultimately sequestered through sediment burial, and some are subjected to oxidation (Bianchi et al., 2018).

Grazing (NTCG) did not show any contrary significant effects on water quality compared to NTC other than lower SRP load and concentration during the first rain event in this study. However, in a related water quality study of an ICL system, grazing significantly decreased surface runoff NO_3^- - N, NH_4^+ - N, PO_4^{3-} - P, and TSS concentrations (Faust et al., 2020). The cattle stocking rates were about 0.41–0.76 ha steer^{-1} compared to 0.01 ha steer^{-1} in the current experiment. The former was continuously grazed, and the latter flash grazed. Like flash grazing that was utilized in this study, a rest rotation grazing system did not reduce infiltration rates nor increase runoff sediment concentrations compared to heavy and moderate continuous grazing techniques (Wood and Wood, 1988). A high stocking density under reduced grazing intensity (like flash grazing) coupled with conservation practices may be sustainable under crop-livestock systems.

4. Conclusion

No-till and cover crops (un-grazed or grazed) improved water quality by reducing surface runoff by up to 6 times CT, significantly curtailing sediment load and total P churned into the environment. Reverting the 12-year-old NT practice to tillage proved to be unfavorable regarding surface runoff and water quality, particularly more so than flash grazing NT systems. The major differences between flash grazing (NTCG) and not grazing (NTC) cover crops that stood out were that the former increased DOC and decreased SRP discharge into the environment compared to the latter. Flash grazing summer cover crops in the semi-arid regions, therefore, provide palatable alternate forage during the off-season without detrimental effects on the soil ecosystem and water quality. Conventional tillage significantly increased concentrations and loads of total solids, total P, and discrete ammonia- and nitrate-N in runoff water. Conservation agriculture practices that promote no-till and use of cover crops (grazed or un-grazed) enhance soil ecosystem service and function, resulting in soil serving as a sink rather than a source of potential agrochemical and atmospheric pollutants to the environment for a more sustainable agricultural production system. Tillage disturbs the soil, leaving it vulnerable to erosion and contamination of surface water. Integrated crop-livestock systems that incorporate grazing cover crops have the potential to spur sustainable production in low-resource input semi-arid regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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