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Short communication

Considerations of a field-scale soil carbon budget for furrow irrigation

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Abstract

There is a general lack of information on the effects of irrigation on soil carbon (C) sequestration in (semi)arid regions. For that purpose we present results of the sediment and C budget of a 30 ha furrow-irrigated corn field in the Central Valley in California. This field was monitored to assess the effects of minimum tillage versus standard tillage on soil C sequestration and greenhouse gas emissions. Water samples of two irrigation events in July and August 2004, were collected and analyzed for suspended sediment, dissolved organic C (DOC) and N (DON), total C and N. Field and soil water budgets were estimated from meteorological data, flow measurements of applied irrigation and runoff water, and neutron-probe soil water measurements. Tail waters contained less sediment but more organic C than irrigation waters, due to particle settlement and enrichment in organic matter. Tillage treatment had no significant effect on composition of water or sediment. Furrow irrigation resulted in a net field input of 700 kg sediment ha^{-1}, 21.4 kg C ha^{-1}, and 7.7 kg N ha^{-1}. The added C by the sedimentation accounted for about two-thirds of the total C increase. The corresponding soil C increase associated with these two irrigation events was about 20% of reported yearly C sequestration rates in long-term soil C sequestration experiments. Our experiments showed the importance of time scale in C budgeting for intensively irrigated agroecosystems, where fast dynamics and large variability of inputs are common.
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Keywords: Carbon budget; Furrow irrigation; DOC; DON; Soil water; C sequestration

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1. Introduction

Soil C sequestration is strongly influenced by land use and tillage. In general, short- and long-term experiments have shown that intensive cropping reduces soil organic matter (SOM) (Mann, 1986). Alternatively, minimum tillage, conservation tillage or non-tillage practices may increase soil organic C (SOC) storage (Campbell et al., 1996), because of improvement of soil structural stability and increased protection of organic matter (Six et al., 1999), thereby increasing biomass production potential (Paul et al., 1997).

Experimental rates of soil organic C (SOC) sequestration by reduced tillage operations typically range from 5 to 25 g C m^{-2} year^{-1} (Ogle et al., 2003; West and Marland, 2002; Six et al., 2002). Among various agricultural landuse practices, changing from dryland to irrigated agriculture will increase soil C storage capacity at the regional scale. Estimates of SOC accumulation in the western region of the U.S. resulting from irrigation vary between 25 and 52 g C m^{-2} year^{-1}, depending on tillage intensity (Eve et al., 2002). Larger water application by irrigation increases biomass productivity and consequently soil C input through residues and roots, changes mineralization rates, and alters the carbonate balance (Watson et al., 2000). Yet, best water, soil, and crop management practices are essential to benefit from irrigation in terms of enhancing productivity and soil C sequestration (Watson et al., 2000).

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The effects of irrigation on the C balance are not clear at the field-scale. Whereas Lueking and Schepers (1985) reported an increase of 11 g C m^{-2} $year^{-1}$ for sandy soils with low SOM content after 15 years of irrigation in Nebraska, irrigation may cause a decrease in SOM in C-rich soils. For example, Dersch and Böhm (2001) concluded that 21 years of supplementary irrigation in Austria decreased SOC between 3.7 and 12.6 g C m^{-2} $year^{-1}$, which was attributed to a higher mineralization rate under the more moist soil conditions. Since the CO_2 emissions can be greater than the equivalent increase in SOC, regardless of tillage type, irrigation is not considered a valid soil C sequestration option in Europe (ECCP, 2003).

Data on soil C sequestration potential for irrigated agriculture in California are scarce, when compared to other regions in the U.S. This is surprising as California is the leading state in agricultural production, with more than 3.5 million ha of irrigated land, increasing with about 0.5 million ha since 1992 (USDA, 2002).

Soil erosion is sometimes disregarded as a mechanism for SOC loss, because C exports from agricultural watersheds cannot always be explained by soil erosion alone (Schlesinger, 1986; Rasmussen and Albrecht, 1998). Moreover, C mobilized by erosion is not always a loss, as redistribution in the landscape provides a mechanism for C burial in the depositional areas of the landscape where C is better preserved (Van Noordwijk et al., 1997; McCarthy and Ritchie, 2002). Yet, there has been little consideration of the contribution of C transported in irrigation and tail waters to assess irrigation effects on soil C sequestration and C budgets at the field-scale, Measures of C losses by soil erosion under furrow irrigation in the western U.S. are reported as high as 3 g C m^{-2} for a single irrigation event (Lentz et al., 1996). However, estimations for the field-scale are difficult to obtain because erosion is spatially variable, with areas of erosion and sedimentation (Trout, 1996) distributed across the same field, whereas much temporal variability is expected during the irrigation season (Brown et al., 1995).

In California, surface water is used on about two-thirds of the irrigated acreage, with the remaining fraction coming from pumping of groundwater (Hutson et al., 2004). The average irrigation efficiency rate of surface irrigation is relatively low, while more than 20% of the irrigated land is serviced by non-lined, open ditches or channels (USDA, 1998). Therefore, the sediment and solute load carried by these surface waters may be a significant component of the field-scale C and N balance. The main objective of this study was to estimate the temporal dynamics of C inputs and outputs of surface-applied water in a furrow-irrigated field, to complement an ongoing C sequestration experiment that evaluates the effects of minimum tillage on soil C sequestration.

2. Materials and methods

2.1. Field site

The study site is a 30 ha furrow-irrigated farmers field (field 74), located in the Sacramento Valley, near Winters, CA. Mapped soil series within the field include a Myers clay (fine, montmorillonitic, thermic, entic chromoxerert) and Hillgate loam (fine, montmorillonitic, thermic, typic palexeralf), which correlate to a Chromic Vertisol and Vertic Luvisol, respectively (World Reference Base for Soil Resources, FAO/ISRIC/ISSS, 1998). The slope of the field is less than 2%. Soil permeability is slow and the $CaCO_3$ content in the topsoil is lower than 5%. The field was split into two equally sized experimental treatments (Fig. 1), representing the grower's standard tillage (ST) and minimum tillage (MT) practices. A sampling grid system was established to yield 70 sampling points in each treatment. A summary of soil textural differences between the two treatments for five depth intervals is presented in Table 1. We conclude that the MT treatment is slightly sandier and has more spatial variation at the larger soil depths because of the occasional presence of sandy pockets.

Irrigation water is delivered by a 15 km long non-lined open channel from Clear Lake and Cache Creek, CA, of Yolo County Flood Control & Water Conservation District (YCFC&WCD; http://www.ycfcwcd.org/index.html). Along its way to the field, drainage and tail water are mixed with fresh water supply. Whereas water application is mostly by surface irrigation, sprinkler irrigation is often used for seed germination. Table 2 shows the main chemical characteristics of the irrigation and tail waters of the experimental field, indicating that these are carbonated waters with low salinity and sodicity levels.

The field was farmed under minimum till for two cropping seasons through July 2003. Using the same 140 sampling locations as for soil texture, a soil C sampling campaign in August 2003 showed that the total C in the top 15 cm was 2280 and 1998 g m^{-2} for the ST and MT treatments, respectively, with corresponding standard deviations of 419 and 388 g m^{-2}. The ST field was tilled

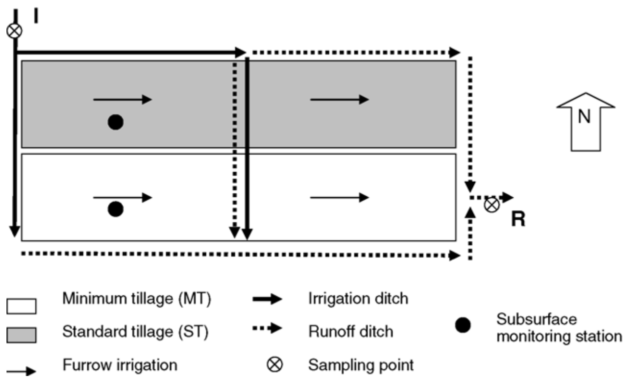

Fig. 1. Sampling scheme of field 74. I: irrigation and R: runoff.

Table 1
Mean and standard deviation (S.D.) of soil texture for ST and MT field

Depth (cm)	Standard tillage (ST)			Minimum tillage (MT)		
	% Clay	% Silt	% Sand	% Clay	% Silt	% Sand
0–15	18.9 (2.6)	55.0 (4.2)	26.2 (6.1)	15.3 (2.5)	48.0 (5.6)	36.7 (7.6)
15–30	20.7 (2.9)	57.4 (3.9)	21.9 (6.2)	17.2 (2.9)	49.5 (6.4)	33.3 (8.9)
30–50	22.2 (3.3)	56.4 (5.6)	21.4 (8.0)	19.1 (3.2)	49.0 (8.1)	31.9 (10.8)
50–75	19.9 (3.3)	54.9 (5.4)	25.2 (8.0)	20.2 (4.7)	49.2 (11.8)	30.6 (15.9)
75–100	19.4 (2.8)	52.4 (6.1)	28.2 (8.2)	19.0 (5.4)	44.9 (13.5)	36.1 (18.5)

Table 2
Chemical properties of irrigation and tail water

	pH[a]	EC[a]	SAR[a]	Ca^{2+}[b]	Mg^{2+}[b]	Na^{+}[b]	Cl^{-}[b]	B^{3+}[b]	HCO_3^{-}[b]	CO_3^{2-}[b]
Irrigation water	8.4	0.3	<1	1.0	1.5	0.7	0.3	0.9	2.2	0.5
Tail water	8.4	0.3	<1	1.1	1.5	0.7	0.4	1.0	2.2	0.5

[a] In dS m^{-1}.
[b] In $mmol_c$ L^{-1}.

in October 2003, and both fields remained fallow until corn (*Zea mays*) planting in April 2004. At planting time, liquid urea/ammonium nitrate (N) was applied through a band application of 56 kg N ha^{-1} at the 10-cm soil depth. Both treatments were side dressed (at 15-cm depth) with 168 kg N ha^{-1} in May 2004. Starting with a pre-irrigation using a moving linear sprinkler system, the fields were furrow-irrigated in six subsequent irrigations for a total amount of applied irrigation water of approximately 1300 mm (Table 3). The duration of each irrigation event was between 2 and 6 days.

2.2. Field monitoring and water sampling

Subsurface measurements were conducted at monitoring stations in each of the two treatments (Fig. 1), starting in May 2004, with measurements generally taken before and after irrigations. Soil water content was determined from readings of a calibrated Troxler neutron-probe at soil depths of 22.5, 45, 75, and 105 cm. Duplicate soil water tension measurements were obtained from tensiometers at depths of 15, 45, 75, and 105 cm. The tensiometers were built from 1-bar standard, 2-in. ceramic porous cups (0655X01-B01M3, Soil Moisture Equipment). Immediately after each irrigation, these tensiometers were temporarily converted to soil solution samplers. Soil solution samples were obtained by applying vacuum with a hand pump and collecting soil solution after 24 h. Water table depth was measured by 135-cm deep observation wells. In addition, a single 285-cm deep piezometer was installed in the ST site.

For irrigation events 6 (starting 7/21/04) and 7 (starting 8/13/04), we obtained daily discharge measurements and water samples at various sampling points across the field to monitor tillage treatment effects. To reduce irrigation water application non-uniformity, the field was split in two halves in the east–west direction. Each of the two sections included a water delivery and tail water ditch. Typically, the first irrigation section was in the NW corner of each field half (Fig. 1), with subsequent sections irrigated in the southern direction. After completion of irrigation of the western half of the field, the eastern half was irrigated, starting in the NW corner as well. Tail water samples were taken from each quarter of the field when irrigated to evaluate tillage effects on water quality (ST and MT samples). However, mostly total field-applied irrigation (I, Fig. 1) and runoff water (R, Fig. 1) volumes and field-average water quality measures

Table 3
Irrigation events of the experimental field

Irrigation event	Date end irrigation	Irrigation depth (mm)	System	Duration (days)
0	20 April	Not measured	Sprinkler	4
1	14 May	207	Furrow	6
2	3 June	233	Furrow	6
3	20 June	216	Furrow	5
4	27 June	86	Furrow	2
5	15 July	170	Furrow	5
6	31 July	207	Furrow	6
7	18 August	181	Furrow	5
Total		1300		39

will be presented, as we found no significant differences between the two tillage treatments.

Most discharge rates in the irrigation and tail water ditches were determined from flow velocity measurements with a current meter, considering the dimensions of the channel network. Estimated travel times of a floating cork were used to estimate water discharges at low water velocity. The coefficient of correlation (R^2) between the discharge measurements of these two methods was 0.65 with a standard error (S.E.) of 0.042 $m^3 s^{-1}$. In addition, we installed a fiberglass 2-in. trapezoidal flume (60° 2-in., Plasti-Fab, Tualintin, OR) in early August 2004, in the main tail water ditch at the down-slope end of the field (*R* in Fig. 1). The flume included a stilling well, through which a pressure transducer was inserted, allowing for continuous tail water discharge measurements at 30-min intervals. The current meter data were validated with the flume measurements. Correlation coefficient and S.E. were 0.97 and 0.0055 $m^3 s^{-1}$, respectively. Water was sampled with 1 L plastic bottles in the center of the ditches, using three replicates for each sampling. Presented data will be average values. The samples were filtered through a pre-burnt and pre-weighted 0.45 μm Millipore glass filter, so that the total suspended solids (TSS) could be estimated. The filtered water and sediments were frozen for further analysis.

2.3. Water and sediment analysis

Sediment samples were ground and analyzed for total C and N with a Carlo-Erba C/N analyzer. Since the weight of the sample needed for such analysis is very small (about 20 mg), all samples were ground and homogenized before the analysis. Sediment samples were corrected for carbonates by HCl fumigation before analysis (Harris et al., 2001). Irrigation and tail waters were analyzed for DOC (UV-persulfate oxidation, Teledyne Instruments Phoenix 8000), total dissolved N (TDN) (Cabrera and Beare, 1993), nitrates (Doane and Horwath, 2003), and ammonium (Forster, 1995). DON was calculated by subtracting nitrates and ammonium from TDN. Soil water was analyzed for total C and N with a DOC/DON analyzer (Shimadzu Corp., Columbia, MD).

2.4. Soil water balance

During the irrigation season the field soil water balance was calculated from the soil water content measurements. Precipitation (P) data were collected from a rain gauge at the field, whereas potential evapotranspiration (ET) data were obtained from a nearby weather station of the California Irrigation Management Information System (CIMIS) in Davis (http://www.cimis.water.ca.gov/cimis/welcome.jsp). Actual crop ET (ET_c) was calculated for corn at maturity using a crop coefficient of $K_c = 1.05$ (Doorenbos and Pruitt, 1977), representative of the growth stage during the measurement period. From water balance calculations, the leaching or drainage losses for the last two irrigations were determined. Moreover, assuming that irrigation efficiency values for irrigation events 6 and 7 are representative, drainage losses to the groundwater for the whole growing season were estimated using the field water balance and farmer-provided irrigation amounts.

3. Results and discussion

3.1. Field water budget

After subtraction of tail water volumes from applied irrigation waters, the net field-average infiltration depths for irrigation events 6 and 7 were both equal to about 135 mm, resulting in irrigation efficiencies of 54 and 75% for irrigations 6 and 7, respectively. The corresponding hydrographs of irrigation and runoff are presented in Fig. 2. All measurements, except for the runoff measurements of event 7, are average daily values. Daily irrigation discharges are variable as the field was irrigated in sections using siphons. Each section was irrigated for between 6 and 12 h. The lag time between the start of irrigation and tail water flow was about 12 h, which may show tail water discharges that are higher than the applied irrigation, such as occurred for July 26 and 29 in Fig. 2. The field water balance for both the ST and MT treatments for the last two irrigation periods is shown in Table 4, with drainage losses computed from effective irrigation depth, precipitation, soil water, and ET_c measurements for each period.

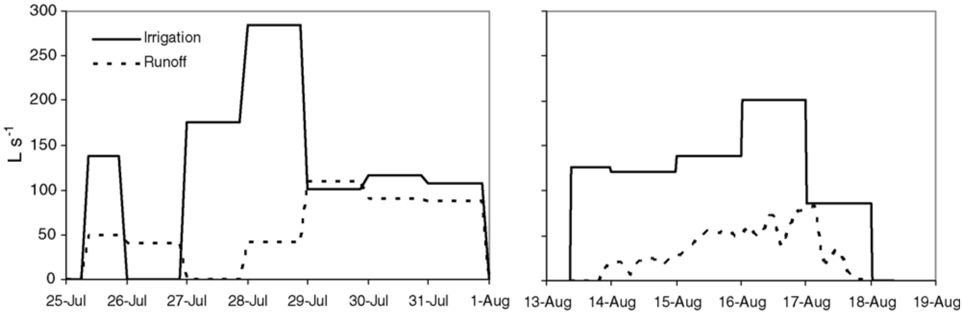

Fig. 2. Hydrographs of irrigation and tail water of irrigation events 6 and 7.

Table 4
Field water balance for the two listed irrigation periods (mm)

Period	ET_c	Net irrigation and rainfall	Soil water storage		Drainage	
			ST	MT	ST	MT
23 July–7 August	100.7	134.9	402.4	410.2	40.4	26.1
7 August–20 August	84.7	134.9	429.5	428.0	23.1	32.4

Positive values of drainage indicate downward flow.

The average irrigation efficiency of the last two irrigation events (0.64) was used to calculate the effective irrigation depth for the other five irrigation events. From water balance calculations, we estimated that net drainage occurred towards the water table for both treatments for most of the time during the irrigation season. Measured groundwater tables were shallow, varying between 0.6 and 1.2 m below the soil surface with the shallowest depths occurring immediately after irrigation. The estimated cumulative ET_c for the growing season, starting on May 1 was 643 mm, while the effective irrigation amount was 862 mm. The estimated total drainage for the same period was higher in the ST (162 mm) than in the MT treatment (116 mm). Differences in head between the water table observation well and deep piezometer of the ST treatment suggest the presence of a shallow perched water table.

3.2. Sediment mass balance

For irrigation events 6 and 7 combined, the average TSS for the irrigation water (I) was 144 mg L^{-1} of sediments, which was four times higher than in the runoff water (R). Concentrations larger than 100 mg L^{-1} will cause clogging in drip irrigation systems, while waters with sediment concentrations less than 50 mg L^{-1} are acceptable (Ayers and Westcot, 1994). Analysis showed that the C associated with the sediments is mainly organic. Fig. 3 presents temporal changes in TSS for the two irrigation events, distinguishing between I and R and ST and MT treatments. No significant differences in TSS were found between the ST and MT treatments. The data show there is high TSS variability in the irrigation water with occasional values larger than 250 mg L^{-1}. Temporal variations in TSS for the irrigation water during and between irrigation events are likely caused by occasional reshaping of water supply ditches before irrigation and the discharge of tail water of upstream fields in the water delivery canal to the farm.

The lower sediment load (SL) in the tail water, as compared with the irrigation water is likely due to the settlement and sorting of the sediment particles in the irrigation furrows, whereas plant residues on the soil surface may act as a filter. Chemical analysis also showed that the C content of the sediments of the runoff water was three times higher than the C content in the sediment of the irrigation water. This might have been caused by occasional algae growth in the tail waters, but more likely by the preferential suspension of the finer material particles with higher C content in the runoff water (Turchenek and Oades, 1979).

The higher sediment concentration of the irrigation water resulted in a net sediment gain of about 250 and 360 kg ha^{-1} for irrigation events 6 and 7, respectively (Table 5 and Fig. 4). Assuming that these would be representative for the irrigation season, the total sediment load to the field would be about 2000 kg ha^{-1} $year^{-1}$. However, one would expect

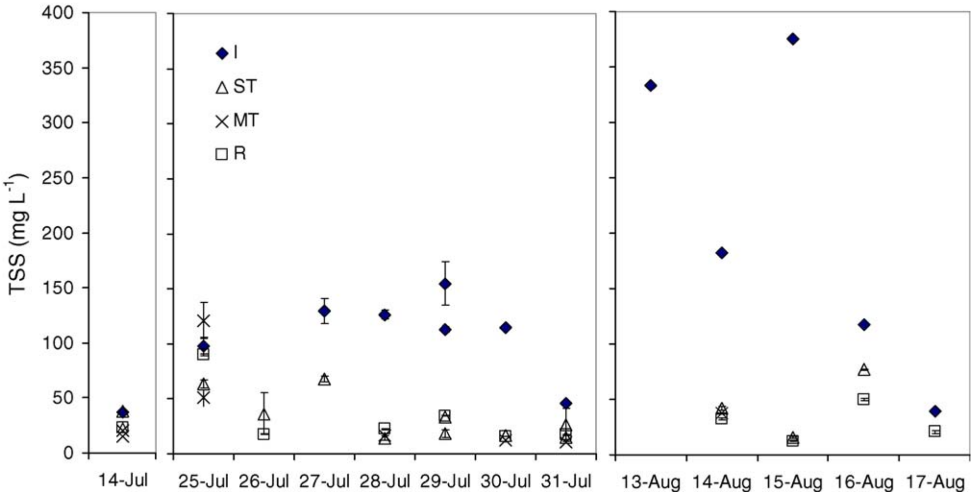

Fig. 3. Total suspended solids (TSS) in irrigation water (I), field runoff (R), and additional tail water samples from ST and MT treatments of irrigation events 6 and 7. Vertical lines represent standard deviations (S.D.) that are partially invisible because of their small size.

Table 5
Total suspended solids (TSS) and sediment load (SL) for the two last irrigation events

Event	Irrigation		Runoff		Sedimentation ($kg\ ha^{-1}$)
	TSS ($mg\ L^{-1}$)	SL (kg)	TSS ($mg\ L^{-1}$)	SL (kg)	
6	111	8359.6	28	974.4	246.6
7	204	11002.1	12	162.6	361.9

net sediment export in the beginning of the irrigation season, particularly for the ST treatment because of tillage operations before and during planting.

3.3. Dissolved C and N

DOC values were generally lower for the irrigation than the tail water (Table 6), which was also the case for the sediments. We did not find a tillage treatment effect. On average, the N-NH_3 contents were very low ($0.03\ mg\ L^{-1}$) compared with DON and nitrates. We explain the enrichment of DOC in the tail water by exchange between irrigation water and plant residue (Lundquist et al., 1999). Possibly, the growth of algae or the higher availability of readily dissolved SOM in the topsoil could have increased DOC in the irrigation water. We also measured large differences in N content between irrigation events 6 and 7, with the irrigation water of event 6 containing almost 10 times more DON and 3 times more nitrates than event 7 (Table 6). The large variations in composition of irrigation water between events are a reflection of the characteristics of the water delivery of the irrigation district, where tail waters are frequently returned to irrigation channels.

The average value of DOC as measured from soil solution samples was about $1.0\ mg\ DOC\ L^{-1}$, which was well below DOC values for the irrigation water ($4.7\ mg\ DOC\ L^{-1}$) or runoff water ($7.8\ mg\ DOC\ L^{-1}$). The DON content was, however, below the detection limit. We therefore suggest that DOC and DON decreased after infiltration, because of mineralization and denitrification. This may be the case for our experimental field, with shallow water tables and excess irrigation.

3.4. Field C and N mass balance

Table 7 presents the estimates of the C and N budgets for the two last irrigation events, considering both DOC and sediment, assuming that the drainage losses were insignificant. Although tail waters were generally higher in DOC than the irrigation water, the total field DOC balance increased by 2.9 and $4.5\ kg\ ha^{-1}$ for the two irrigations, respectively. The corresponding net gains in N were 5.2 and $0.8\ kg\ ha^{-1}$. When considering sediment only, each of the two irrigations resulted in a C addition of about $7\ kg\ ha^{-1}$. The corresponding net gains in N from SOM in the sediment were 0.70 and $0.90\ kg\ N\ ha^{-1}$ for each irrigation event. The two irrigation events combined resulted in a net field addition of C and N of $21.9\ kg\ C\ ha^{-1}$ and $7.6\ kg\ N\ ha^{-1}$, respectively. We expect that the C and N of the sediment is more stable and protected than in the dissolved fraction.

4. Summary and conclusions

The two surface irrigations during the 1-month study period resulted in C and N additions of $21.9\ kg\ C\ ha^{-1}$ and $7.6\ kg\ N\ ha^{-1}$. Although these amounts are not large for agronomic purposes, they can be significant within the context of C sequestration. Carbon gains for this short period represent about 20% of reported yearly C sequestration rates in published long-term experiments. The implications of this added amount of C for the release of greenhouse gases depend on the C source. The soil solution contained very low amounts of C and no N, suggesting that DOM in infiltrating waters is readily mineralized and denitrified. No significant

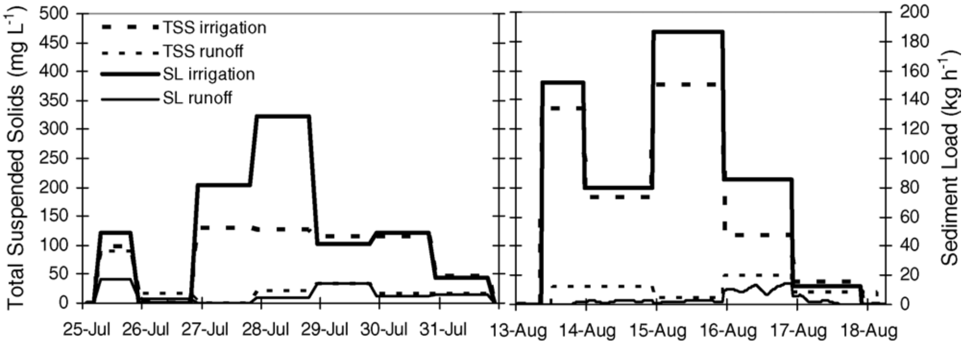

Fig. 4. Total suspended solids (TSS) with corresponding sediment load (SL) for irrigation and runoff water of irrigation events 6 and 7.

Table 6
Average DOC, DON and N-NO_3^- contents and C/N ratios of the dissolved organic matter of irrigation and tail water for the two last irrigation events

Irrigation event	DOC (mg L^{-1})	DON (mg L^{-1})	N-NO_3^- (mg L^{-1})	C/N	Number of samples
I	4.71 a	1.79 a	0.94 a	7.1 a	12
R	7.81 b	1.89 a	1.07 a	7.5 a	10
ST	6.81 ab	1.95 a	1.14 a	10.0 a	12
MT	6.40 ab	1.72 a	1.60 a	9.7 a	6

I: irrigation water, R: total runoff, ST: runoff of standard tillage, MT: runoff of minimum tillage. Values followed by the same letter (a and b) in the same column within each block are not significantly different at a $p < 1\%$.

Table 7
Field mass balance of C and N (kg ha^{-1}) for the two last irrigation events

Event		C[a]	DON	N-NO_3^-	N-NH_4^+	Total N
6	Water					
	Irrigation	12.4	6.8	3.5	0.11	10.4
	Runoff	9.5	3.1	1.9	0.05	5.0
	Net increase	2.9	3.7	1.5	0.06	5.2
	Sediment[b]					
	Irrigation	10.1				1.0
	Runoff	2.6				0.3
	Net increase	7.5				0.7
	Total	10.4				5.9
7	Water					
	Irrigation	8.0	0.7	0.7	0.04	1.4
	Runoff	3.5	0.3	0.3	0.01	0.6
	Net increase	4.5	0.4	0.4	0.03	0.8
	Sediment[b]					
	Irrigation	7.5				1.0
	Runoff	0.5				0.1
	Net increase	7.0				0.9
	Total	11.5				1.7
6 and 7		21.9				7.6

[a] Total C in sediment samples and DOC in water samples.
[b] Partitioning of N not available.

differences were found between tillage treatments, likely because tillage differences were established only one year before sampling. Moreover, our data show high temporal variability in suspended solids and dissolved components. The limited information collected to date show that the variations of C input by irrigation may mask the effects of tillage or management practices on soil C sequestration. Our data also indicate that variations in sediment and C content of irrigation and tail water between fields may be large. Yet, our results clearly show for the first time that C imports by irrigation water must be considered in field-scale C sequestration studies.

In spite of the limited sampling, our results show that surface irrigation should be considered in the development of seasonal field-scale sediment, C and N budgets. The amounts of these components carried by irrigation water in the two last irrigation events were highly variable in time. Therefore, detailed sampling of irrigation and tail waters is recommended to estimate field-scale sediment, C and N budgets.

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