Pros and cons of furrow irrigation on smallholdings in northeast Brazil

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ABSTRACT

Smallholder farming is the basis of agricultural production in developing regions. Irrigation improves the household livelihood and welfare of smallholders. Furrow irrigation is the most common type of irrigation on the small farms of public irrigation schemes set up in the Northeast of Brazil during the 1970s and 1980s. However, furrow irrigation triggers environmental problems related to deep percolation, runoff and soil erosion. The objective of this research was to determine how soil was lost from irrigation furrows as a result of their management and performance. Experiments were carried out in the Curú-Pentecoste irrigation scheme located in the state of Ceará, Brazil. Three inflow rates (corresponding to the three sizes of syphons used to apply water to the furrows) were compared on 60-m long furrows in the two predominant soil classes (sandy loam and silty clay loam) during 4 or 5 irrigation events throughout the irrigation season. Runoff represented between 20 and 70 % of the water applied, carrying sediments amounting up to 2.8 Mg ha⁻¹ in 4 irrigation events. Simple irrigation practices that could improve furrow irrigation performance in the scheme are suggested. However, the environmental problems of the furrow irrigation in practice seem inherent to the irrigation method used under those conditions. The paper discusses the adoption and performance of traditional and modern irrigation technology in smallholdings in developing regions.

1. Introduction

Worldwide, over 324 million hectares were equipped for irrigation in 2012, of which about 275 million ha were actually irrigated (FAO, 2016). Localized and sprinkler irrigation accounted for only about 14 % of this area, the remaining area being systematized for surface irrigation methods (FAO, 2016), that include furrow, border and basin irrigation. The first of these is the most common type of surface irrigation for row crops on small farms in developing regions (Kay, 1986).

Smallholder farming is the basis of agricultural production in developing countries. At least 90% of farms in the world are family farms, occupying between 50% (Graeub et al., 2016) and 75% (Lowder et al., 2016) of the world's agricultural land. The number of these farms that have irrigation is unascertained, but it is well known that irrigation improves household livelihood and welfare of smallholders (Hussain and Hanjra, 2004; Connor et al., 2008; Hanjra et al., 2009; Hussain, 2007; Comas et al., 2012; Burney et al., 2013; Burney et al., 2014).

The Brazilian public irrigation schemes (schemes funded by the government) concentrated in the semi-arid Northeast, occupy 219,000 ha of a total of 7 million ha, and serve a large number of smallholders in one of Brazil's poorest regions (ANA, 2017). However, public schemes are stigmatized for their poor performance and while irrigation (public plus private) in Brazil is expanding at a rate of about 5 %/y (probably the highest rate worldwide), the area of public schemes has only increased by about 2 %/y (ANA, 2017). Gonçalves et al. (2015) evaluated a large sample of these schemes finding a great variation in their performance, that they attributed to the predominant type of the on-farm irrigation system. Micro irrigation (surface drip and micro-sprinkler systems) was the principal system on the farms of the scheme that performed best, while the Curú-Pentecoste irrigation scheme showed the worst performance due to the preponderance of surface irrigation.

Supported by these and other findings, international scholars have claimed the excellence of micro irrigation for smallholders in Sub-Saharan Africa, Asia, and Latin America (Postel et al., 2001). However, recent studies are rebutting this claim (Wanvoeke et al., 2015; Venot et al., 2018). Mateos et al. (2018) have contributed to the debate with a case study in northeast Brazil. These authors evaluated irrigation performance on family farms of a modern public scheme where all the farms use micro irrigation. The study identified "technology translation" gaps that explained the overall poor performance of these modern micro irrigation systems. Determining the reasons for the ineffective performance, and the links to the appropriateness of the on-farm system selected, is crucial for sustainable and socially just irrigation development. Research on smallholder surface irrigation performance in Brazilian public irrigation schemes is therefore needed to make advances in understanding them.

Although surface irrigation is the oldest irrigation method, the physical processes involved have only been mathematically formulated relatively recently (Strelkoff and Clemmens, 2007). Field measurements and hydraulic models have contributed to a better understanding of furrow irrigation performance itself (Bautista et al., 2009) and in comparison with other irrigation methods (Mateos, 2006). In furrow irrigation, the distribution of water across the field is simultaneous to its infiltration, which makes distribution uniformity and application efficiency highly dependent on the variability of soil characteristics (Bautista and Wallender, 1985; Izadi and Wallender, 1985; Oyonarte and Mateos, 2002). The inflow rate must be sufficient to ensure that water advances to the tail of the furrows in a reasonable time in order to allow sufficient water infiltration and uniformity throughout the field. As water flows along the furrows, it detaches soil particles that are transported downstream (Trout, 1996; Trout and Neibling, 1993; Fernández-Gómez et al., 2004; Mateos and Giráldez, 2005). Water that does not infiltrate runs off the field entering nearby water bodies. Therefore, furrow irrigation poses a number of environmental problems that include inefficiency, soil erosion, and water pollution.

The objective of this study is twofold. First, to contribute to the understanding of the erosion and soil loss processes in irrigation furrows, relating them to irrigation efficiency, infiltration uniformity, and the irrigation operation itself. Investigation on the erosion of irrigation furrows has been very scarce to date (King et al., 2015). This work provides new data in different soils and in the smallholder context, and does so following the approach used by Fernández-Gómez et al. (2004). Second, the discussion aims to contribute to the debate on which irrigation method is the most appropriate one for small farmers, introducing soil loss as an environmental performance criterion.

2. Material and methods

2.1. The Curú-Pentecoste irrigation scheme

The study case is the Curú-Pentecoste irrigation scheme (CPIS), located in the semiarid Brazilian North-East, in the state of Ceará (between latitudes 3° 40' and 3° 51' 18'' S and longitudes 39° 10' 19'' and 39° 18' 13'' W, Fig. 1). The scheme was set up between 1974 and 1979, and it started operating in 1975. CPIS has a tropical climate with dry summers and rainfall concentrated between February and May (INMET, 2018). The mean annual rainfall is of 770 mm. Soils, of an alluvial origin, are classified as *Luvissols* or *Fluvic neosols* (FAO, 2006), and have a silty clay loam or sandy loam texture. The main crops are banana, coconut, papaya and cowpea. Water is supplied by the General Sampaio and Pereira de Miranda reservoirs in the Curú River. Two main canals (P1 and P2, with a capacity of 1.8 m³ s⁻¹ and 0.8 m³ s⁻¹,

respectively) divert water from the Serrota weir to convey it to the scheme. The water is distributed by gravity through secondary canals. The irrigable area in CPIS is 1180 ha and the area actually cultivated is 743 ha, of which 715 ha belong to 173 family farms with an average size of 4.13 ha. On-farm irrigation is by furrows. All the farmers belong to a cooperative in charge of the management, operation and maintenance of the scheme.

To characterize the on-farm irrigation, we conducted a field survey in eight farms. Farmers were questioned about irrigation turns, farm outlet flow rate, furrow characteristics (length, slope, grading), water application method (syphon, perforated pipe, others), irrigation equipment cost, furrow irrigation time, irrigation frequency and hydraulic head of the syphons.

2.2. Experimental sites and treatments

The experiments were conducted in two relatively flat sites of the Experimental Farm Curú Valley, located in CPIS. The sites selected represented the main soils in CPIS: sandy loam (Site 1) and silty clay loam (Site 2). Other soil characteristics are in Table 1.

The experimental period was July-October 2010 and 2012 in Sites 1 and 2, respectively. The furrows were planted with cotton in 2010 and left bare in 2012. There was no rainfall during the experimental periods. Mean reference evapotranspiration during the period of maximum cotton groundcover was estimated at 3.8 mm day⁻¹ (mean value for September at the Guaramiranga station, the weather station in the CLIMWAT database nearest to CPIS; FAO, 2018), although in CPIS it is likely to be higher, because it is in the transition from the “Tropical savanna and dry climate (As)” to the “Hot semi-arid climate (BSh)”, according to the Köppen-Geiger climate classification (Beck et al., 218). Assuming a crop coefficient of 1.1, net irrigation requirements (Z_{req} , mm) of cotton for an irrigation interval of 8 days are $1.1 \times 3.8 \text{ mm day}^{-1} \times 8 \text{ day} = 34 \text{ mm}$.

The length, spacing and slope of the furrows were selected based on the survey, with the aim of representing the typical characteristics of the furrows in CPIS. The area of the experimental plots was 1500 m². Each plot consisted of 29 furrows 63-m long, 0.8-m apart (Fig. 2). Water was applied by syphons fed from a secondary canal, and runoff was collected in a drain ditch along the furrows’ tail.

The treatments were the inflow rates given by syphons with diameters of 1, 1.5 or 2 inches (25.4, 38.1 and 50.8 mm, respectively). Each treatment (named Q1, Q2, and Q3, respectively) consisted of seven adjacent furrows, three of which were monitored (alternating monitored and non-monitored furrows). Each 7-furrow set was flanked by pairs of non-irrigated furrows used to access to the measurement locations (Fig. 2). Cutoff time (the time at which the supply of water is interrupted, t_{co} , min) was the advance time (t_{adv} , min) plus 40 minutes (based on the

common practice in CPIS explained in section 3.1). The number of irrigation events monitored was five in Site 1 and four in Site 2.

2.3. Measurements

Inflow (Q_{in} , $\text{m}^3 \text{min}^{-1}$) and outflow (Q_{out} , $\text{m}^3 \text{min}^{-1}$) were measured periodically (times t , min) during the irrigation events using Parshall flumes with a throat 24.5 mm wide (USBR, 1997). The head flumes were located at about 3 m from the supply channel. The distance from the head to the tail flumes was $L = 60$ m, the furrow length monitored. Stakes placed every 10 m marked the distances from the furrow head (l , m) of the i th advance ($t_{a,i}$, min) and recession ($t_{r,i}$, min) time observation stations.

Runoff water samples were collected in 0.5-L containers at the outlet of each tail flume at times (t , min) 1, 3, 5, 10, 15, 25, 35, 40, 45, and 50 minutes after advance time. Q_{out} was measured at the same times until t_{ends} , assumed to be equal to t_{adv} plus 50 min. The samples were dried in an oven at 105°C. The dry samples were weighed and the sediment concentration computed.

The longitudinal profile of the furrows monitored in both Sites was determined after soil preparation. The furrow cross-sectional geometry was determined in Site 1 before the first irrigation event and after the last one, using a furrow profilometer placed at fixed positions at distances from the head flume of 5, 10, 15, 20, 30, 40, 50 and 60 m.

2.4. Performance indicators

The irrigation performance indicators selected for the assessment were application efficiency (E_a , %), tailwater ratio (TWR , %), deep percolation ratio (DPR , %), and water requirement efficiency (E_r , %) (Walker and Skogerboe, 1987):

$$TWR = 100 \frac{V_{ro}}{V_{app}} \quad (1)$$

$$DPR = 100 \frac{V_p}{V_{app}} \quad (2)$$

$$E_a = 100 - TWR - DPR \quad (3)$$

$$E_r = 100 \frac{V_c}{V_{req}} \quad (4)$$

where V_{req} (m³) is the volume of required water and the volumes of applied water (V_{app} , m³), runoff (V_{ro} , m³), infiltration (V_{inf} , m³), percolation (V_p , m³) and crop available water (V_c , m³) were calculated as:

$$V_{app} = \int_0^{t_{co}} Q_{in} dt \quad (5)$$

$$V_{ro} = \int_{t_{adv}}^{t_{end}} Q_{out} dt \quad (6)$$

$$V_{inf} = \int_0^L Z_{inf} dl = V_{app} - V_{ro} \quad (7)$$

$$V_p = \int_0^L \max[(Z_{inf} - Z_{req}), 0] dl \quad (8)$$

$$V_c = \int_0^L \min[Z_{req}, Z_{inf}] dl \quad (9)$$

The infiltrated depth was estimated at each i th station (Z_{inf} , m³ m⁻¹) using Kostiakov-Lewis equation as in Walker and Skogerboe (1987):

$$Z_{inf,i} = k(t_{r,i} - t_{a,i})^a + f_o(t_{r,i} - t_{a,i}) \quad (10)$$

where f_o (m³ m⁻¹ min⁻¹) is the basic infiltration rate and k and a are empirical parameters. The value of f_o was estimated by dividing by L the difference $Q_{in} - Q_{out}$ computed once the outflow rate was stabilized. The parameters k and a were obtained for each furrow/irrigation event using the WinSRFR surface irrigation analysis programme (Bautista et al., 2009; available at the USDA-ARS website <http://www.ars.usda.gov/services/software/software.htm>). Furrow geometry, roughness parameter (Manning's roughness parameter was assumed to be equal to 0.04 for the first irrigation events and 0.02 for the successive events), and the inflow hydrograph were entered in WinSRFR and the values of k and a modified manually until matching the simulated and observed advance and recession trajectories while maintaining the simulated V_{ro} equal to the measured V_{ro} .

Infiltration uniformity was quantified with the indicator distribution uniformity (DU , %), the ratio of the average of the depths infiltrated in the quarter of the length of the furrow that receives the smallest depths and the average depth infiltrated along the entire length of the furrow (Burt et al., 1997):

$$DU = 100 \frac{4V_{inf,lq}}{V_{inf}} \quad (11)$$

where $V_{inf,lq}$ is the volume of water infiltrated in the quarter of the furrow length receiving the smallest depths (low-quarter, indicated with the subscript lq):

$$V_{inf,lq} = \int_{\frac{3}{4}L}^L Z_{inf} dl \quad (12)$$

A sixth performance indicator was soil loss (SL , $Mg\ ha^{-1}$):

$$SL = \frac{\int_{t_{adv}}^{t_{end}} C Q_{out} dt}{100 L s} \quad (11)$$

where C is the concentration of sediments in the runoff water expressed in $g\ m^{-3}$.

The integrals in Eqs. 5-9 and 12-13 were computed with the trapezoidal rule (Abramowitz and Stegun, 1972).

All performance indicators were normalized to a target-infiltrated depth of 34 mm (the net irrigation requirement; see section 2.2) at the tail of each monitored furrow for all irrigation events. This was necessary to make the treatments comparable since irrigation time and infiltrated depth varied from treatment to treatment, among furrows in the same treatment, and among irrigation events. The target depth of 34 mm at the furrow tail was consistent with the usual CPIS practice of allowing 40 min of runoff and implied $E_r = 1$.

3. Results

3.1. Furrow irrigation in CPIS

The delivery schedule in CPIS is in turns, at intervals of eight days. Typically, the flow rate at the farm outlets is about $2.4 \text{ m}^3 \text{ min}^{-1}$, the duration of the turn about 12 hours, and the area served by one outlet is about 2 ha. Therefore, the water depth that one farm outlet can supply during an irrigation turn is $2.4 \text{ m}^3 \text{ min}^{-1} \times 12 \text{ h} \times 60 \text{ min h}^{-1} \div 2 \text{ ha} = 86 \text{ mm}$.

The water is applied to the furrows directly from secondary canals using syphons with diameters of 1, 1.5 or 2 inches (25.4, 38.1 and 50.8 mm, respectively) and a length of about 2 m. The hydraulic head is around 0.2 m. The most common furrow length varied between 80 and 100 m and the slope between 0.2 and 0.5 %. Grading was rare. Cutoff time was typically around 40 minutes after the end of the advance phase.

The only irrigation equipment utilised are syphons, that are moved from furrow set to furrow set and from field to field. Therefore, for the flow rate of $2.4 \text{ m}^3 \text{ min}^{-1}$ at the farm outlet, the farmer would need a set of about 40 syphons of one inch per farm outlet. The cost of a syphon is about US\$ 6.00. Since the land in CPIS is relatively flat, furrow irrigation is done without grading or levelling, or after little earth movement. Therefore, furrow irrigation management in CPIS is inexpensive and simple once the irrigator has acquired some experience.

3.2. The furrow irrigation process in the experimental sites

Water that flows into the furrow head advances at a rate that depends on furrow slope, inflow rate and soil infiltration characteristics. Fig. 3 depicts the process for one of the furrows on Site 1, during Irrigation I, under treatment Q1. Typically, the advance trajectory follows a potential function (Fig 3a). After cutoff time, the water on the furrow recedes. Compared to the advance trajectory, the recession trajectory is typically quite flat. [Recession in our experiments was rapid, thus it was assumed to occur at cutoff time all along the furrow length (Fig. 3a).] While water advances and recedes, it infiltrates into the soil. The infiltration opportunity time is therefore greater at the head than at the tail, so that the infiltrated depth varies correspondingly (Fig. 3b). This source of non-uniformity is inherent to furrow irrigation. Runoff starts when the advance front reaches the furrow end (Fig. 3c). At that time, sediment concentration in the runoff water is typically high, although it decreases rapidly as runoff progresses until reaching a roughly constant value (Fig. 3c).

However, the furrow slope, inflow rate and soil infiltration characteristics are variable. Figure 4 shows the mean and variability of the longitudinal profile of the furrows monitored in Sites 1 and 2. The total gradient in them was 0.47 % and 0.32 %, respectively. The slope was quite constant along the furrows in Site 2, but in Site 1 the slope at the furrow head and tail was steeper than in the middle reach (Fig. 4).

The mean inflow rate supplied by the syphons with diameters of 1, 1.5 and 2 inches was 0.042, 0.105 and 0.165 m³ min⁻¹, respectively. The inflow rate also varied significantly among furrows and irrigations (range of variation 0.035-0.049, 0.090-0.122, 0.132-0.202 m³ min⁻¹ in Q1, Q2, and Q3, respectively), as depicted in the box plot chart of Figure 5. Various factors could cause this variability, among which the difference in elevation between the water surface in the supply canal and the syphon outlet would be the most important one.

The inflow rate treatments had a direct effect on advance time. The water flowed faster in treatment Q3 (mean inflow rate of 0.165 m³ min⁻¹) than in Q2 (0.105 m³ min⁻¹), and in Q2 faster than in Q1 (0.042 m³ min⁻¹), although advance time was more sensitive to the inflow rate in its lower range (Fig. 6). The intra-treatment variability of slope, inflow rate and soil characteristics was translated into the variability of the advance time. Figure 6 shows advance time variability from irrigation to irrigation for a given inflow rate treatment and the standard deviation bars indicate variability among the furrows of each treatment and irrigation event.

The advance time was a little longer than runoff time (40 min) in Q1 (mean advance time in Q1 was 47 min), while in Q2 and Q3 the wetting phase was notably longer than the advance phase (mean advance time in Q2 and Q3 was 6 and 12 min, respectively). Mean applied water was 77, 126 and 167 mm in Q1, Q2 and Q3, respectively. Therefore, the supply capacity of the typical CPIS farm outlet (86 mm; see section 3.1) could meet the water requirement under strategy Q1 even with the entire area (2 ha) under irrigation; strategy Q3 would be feasible if not more than half of the area was irrigated; and strategy Q2 would be feasible with up to two thirds of the area under irrigation.

After a certain wetting time, infiltration was stabilized and the outflow rate reached a constant value for each furrow. The difference between the stabilized inflow and outflow rates allowed the calculation of the basic infiltration rate for each furrow monitored. This rate varied greatly between sites and from furrow to furrow (Fig. 7). It showed some correlation with the inflow rate for each treatment; however, the relationship was different between treatments. This striking behaviour was observed in both sites and was not related to a decrease in the basic infiltration rate as the number of irrigation events accumulates throughout the season, as other authors have observed (Mateos and Oyonarte, 2005).

3.3. Soil loss vs. irrigation performance

The treatments had a clear effect on soil loss. Figure 8 depicts soil loss accumulated during the 5 and 4 irrigation events monitored in Site 1 and Site 2, respectively. The largest soil loss, observed in Site 2 under treatment Q3, was 2.8 Mg ha⁻¹ in 4 irrigation events. Soil loss in Site 1 (sandy loam) was, on average, lesser than in Site 2 (silty clay loam) for all treatments despite

the former receiving one more irrigation and being slightly steeper. However, soil loss variability in Site 2 was much greater than in Site 1. Furrow 1 of treatment Q2 and furrow 3 of treatment Q3 yielded anomalously large soil losses in all irrigation events in Site 2.

Figure 9 depicts soil loss vs. distribution uniformity and application efficiency computed for each furrow monitored, showing a wide variety of situations. In both sites, maximum DU was around 95 %, while minimum DU was around 70 %, the lowest values occurring under Q1 and the highest under Q2 (Site 2) or Q3 (Site 1). Soil loss tended to increase with DU , although the correlation was weak in Site 2 (Fig. 9). Q1, the treatment that clearly yielded less soil loss, had a mean DU of about 81 %, against a mean DU of 90 % in Q2 and Q3. The maximum DU under Q2 (not under Q3) in Site 2 was unexpected. Thorough examination of the data revealed that this was due to the low basic infiltration rate observed in several irrigation events on block Q2 (particularly irrigations I and II). This also contributed to the high soil loss observed in furrow 1 under Q2: the low infiltration rate obliged to a long wetting phase (to meet the target infiltrated depth), which, in turn, implied a large soil loss. Soil heterogeneity was therefore the cause of the large scatter observed in Fig. 9, which was greatest in Site 2. Furthermore, the infiltrated depth used to compute DU varied along the furrow with opportunity time only, that is, the infiltration variability due to the heterogeneity of soil infiltration characteristics was not taken into account. DU was therefore an upper limit of actual infiltration uniformity.

Mean E_a in Site 1 was 53, 41 and 39 % under Q1, Q2, and Q3, respectively, although scatter was also considerable (Fig. 9a), to the point that the two highest values of E_a were observed in Q2 and Q3. In Site 2, the scatter was even greater than in Site 1 (Fig. 9b). Mean E_a in Site 2 was 47, 32 and 47 % under Q1, Q2, and Q3, respectively. Highest E_a corresponded to relatively low TWR (less than 35 %) (Fig. 10ab) and relatively high DPR (DPR was generally less than 20 %, data not shown) in both Sites. Conversely, the lowest E_a corresponded to furrow irrigation events with high TWR despite DPR being low. Globally, a large soil loss was associated with high DU , low E_a , high TWR , and low DPR , conditions more typical of Q2 and Q3 than of Q1.

Although DU in Q1, the treatment that conserved most soil, was lesser than in Q2 and Q3, non-uniformity could not affect crop growth (remember that the irrigation strategy imposed $E_r = 100$ %).

4. Discussion

Smallholder farmers, over the years, have acquired furrow irrigation experience, an inexpensive way of watering crops. However, potential performance of furrow irrigation has inherent limitations. Furrow infiltration variability is usually estimated based only on the variation of the

infiltration opportunity time along the furrow (Walker and Skogerboe, 1987). However, this source of variability is likely to be a minor one compared with that due to inflow rate variability (Trout, 1990) or to soil heterogeneity, particularly where the furrows are short and the advance time is a small fraction of the application time, as happens in CPIS. In our experiments, advance time varied from about 10 min (Q1) to about 50 min (Q3), with application times varying from approximately 50 min to 90 min, respectively. With advance and application times of this order of magnitude, Childs et al. (1993) found that on considering the soil infiltration characteristics to be variable and the opportunity time to be constant, the coefficient of variation of the infiltrated depth was between 1.5 and 5 times greater than when considering the soil to be homogeneous and the opportunity time variable. Similarly, Oyonarte et al. (2002) found that soil infiltration characteristics accounted for 45-71% of the variance of infiltrated depth under first irrigation conditions, and for more than 76% in subsequent irrigations. In addition, Boulal et al. (2011a) observed that infiltration is very much affected by soil management. The variability among furrows of the basic infiltration rate exhibited in Figure 7 is an additional source of infiltration variability across the field that superimposes the in-furrow variability. Moreover, Figure 7 shows another unexpected source of infiltration non-uniformity across the field: the correlation between f_o and Q_{in} was different for the different ranges of Q_{in} tested there. This phenomenon could be due to a neighbourhood effect: what distinguishes one furrow with a given flow rate in one treatment from furrows with the same or similar flow rate in another treatment is that each of them are flanked by furrows with flow rates of a different magnitude. The possible neighbourhood effect would be probably related to differences in the wetted perimeter, another factor that influences furrow infiltration (Izadi and Wallender, 1985; Oyonarte et al., 2002). Another possible cause of this phenomenon could be erosion itself, which could cause surface sealing at high inflow rates (Trout and Mackey, 1988). The corollary is that when soil characteristics that affect infiltration variability are taken into account, furrow irrigation performance is significantly poorer than when, like in the standard evaluation procedure, they are ignored.

The trade-offs between distribution uniformity and application efficiency (Fig. 9) and between the tail water and deep percolation ratios (Fig. 10) entail nutrient leaching, on one hand, and runoff, soil loss and surface water pollution, on the other. Runoff seemed to be a major cause of inefficiency and of environmental damage caused by furrow irrigation. The mean soil loss accumulated during the 5 and 4 irrigation events monitored in Sites 1 and 2, respectively, ranged between 0.25 and 2.80 Mg ha⁻¹ (Fig. 8). Considering that the typical number of irrigations would be about twice the number of irrigations monitored, the annual irrigation-induced soil losses in the Q3 treatment would be below the soil loss tolerance of 12 Mg ha⁻¹ y⁻¹ established by the USDA Natural Resources Conservation Service (1999) for this kind of soil.

However, this threshold is only based on soil productivity and soil formation rate, ignoring the off-site effects of soil erosion (Li et al., 2009). Therefore, irrigation on the soils of CPIS must be carefully managed given their susceptibility to erosion, especially the sandy loam soils.

Treatment Q1 could represent the best compromise between irrigation performance indicators and soil loss. In spite of that, the environmental impact associated with irrigation runoff and deep percolation deduced from Figures 9 and 10, and aggravated by poor drainage, questions the sustainability of current irrigation practices in CPIS (Albuquerque et al., 2018). Furrow irrigation could be improved in CPIS by using small-diameter syphons and carrying out cutback flow. An irrigation advisory service could easily promote those syphons. Cutback flow would alter current practices, so it would require some effort from the advisors, but it could be an easy and effective method to reduce both deep percolation and runoff (Gudissa and Edossa, 2014). In CPIS, the cutback method could be implemented by placing two small-diameter siphons at the head of each furrow, for rapid water advance, and then removing one of them, to complete irrigation with a reduced outflow rate (Kay, 1986). Other measures to improve furrow irrigation performance could be blocked-end furrows (where feasible), laser levelling (although its cost per area in smallholdings could be significant) and reusing runoff water (which would require new infrastructures such as regulation reservoirs and pumps).

Furrow irrigation performance in CPIS is not encouraging and suffers from the same predicament as other irrigation technologies elsewhere. The performance of furrow irrigation in CPIS is no better than that of micro irrigation in the nearby Baixo Acaraú irrigation district (Mateos et al., 2018). Poor performance or success of modern irrigation systems such as drip irrigation (Wanvocke et al., 2015; Venot et al., 2018) could be better contextualized if compared with that of traditional surface methods. Although the soils allocated for irrigation in CPIS are good alluvial ones, suitable for surface irrigation, experiments carried out in the district showed that drip irrigation was able to increase pumpkin yield significantly using considerably less water than furrow irrigation (Santos et al., 2010). However, irrigation performance has to be related to the technological context, to the actual irrigation practices, and to the farmer's decision-making process (Benouniche et al., 2014a). An open innovation environment may favour the adoption of good irrigation practices, the adaptation of modern technology to local needs (Poncet et al., 2010; Benouniche et al., 2014b), and the "technology translation" flow (Garb and Friedlander, 2014). Improved irrigation practices can be envisaged even for traditional surface irrigation. For instance, the cutback flow could be adopted in CPIS through local adaptation. However, the evidence has shown that this has not happened yet. The Brazilian government constructed CPIS in the 1970s to improve the livelihood of farmers who did not have any previous irrigation experience. Farming was supported with well-trained engineers and

agronomy advisors. Unfortunately, the government withdrew this support during the 1980s, so farmers lost their capacity to adopt good irrigation practices and to innovate.

Collective irrigation schemes are normally designed and managed for specific on-farm irrigation methods, i.e. surface irrigation in CPIS. In turn, Gonçalves et al. (2015) attributed the poor performance of CPIS to the on-farm irrigation method. Moreover, the delivery and maintenance service initially provided by CPIS was drastically reduced in the 1980s. Insufficient maintenance and deficient operation usually trigger the degradation spiral that has been described for other irrigation schemes in developing countries (Garcia-Bolaños et al., 2011; Borgia et al., 2013). On the other hand, transforming a collective gravity system into a pressurized one, for micro or sprinkler irrigation, may not be successful, is expensive, and precludes surface irrigation. Furthermore, the improvement of global (irrigation and environmental) efficiency would be largely affected by the hydrological setting and layout of the irrigation scheme (Mateos, 2008). Therefore, when dealing with collective irrigation schemes, the debate about which irrigation method best fits smallholder's needs has to go beyond the farm context. Alternative approaches allowing the coexistence of on-farm gravity and pressurized irrigation would satisfy a diversity of smallholder needs and farming strategies and would favour more open innovation. Modern decision support systems would then become essential management tools (Lozano and Mateos, 2008).

5. Conclusions

Furrow irrigation is a low-cost technology that smallholders can afford. The cost of the equipment necessary to irrigate 2-ha blocks in CPIS with the typical flow rate of $2.4 \text{ m}^3 \text{ min}^{-1}$ at the farm outlets is about US\$ 300 (syphons plus hoes). Moreover, once the irrigator has acquired some practice, furrow irrigation is relatively easy to operate compared to modern micro irrigation systems. However, furrow irrigation poses some important environmental problems; runoff in the experimental sites represented up to 70 % of the applied water (ranged from 20 to 70 %). This runoff was able to carry sediment loads of up to 5.6 Mg ha^{-1} in an irrigation season on Site 2 (silty clay loam soil with slope of 0.32 %).

Irrigation performance and soil loss notably varied in the experiments, so we assumed that the range of variation observed covered what can be found in CPIS. There were no performances that could be described as good. Notwithstanding, we could suggest simple practices (e.g., reducing the size of the syphon or carrying out cutback flow) that could significantly improve furrow irrigation performance in CPIS. We contend that, with public support, irrigation advisory services (Córcoles et al., 2016) could help to introduce such practices.

While recent studies have questioned both the potential of drip irrigation to save water and its adaptability to smallholders' needs, our study shows serious environmental problems that are in practice inherent to traditional surface irrigation. This conclusion contributes to the debate about the adoption and performance of new irrigation technology on smallholdings of developing regions and about the transformation of collective gravity systems into pressurized ones.

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554 Table 1. Soil characteristics (0-30 cm) in the two experimental sites.

	Site 1 (sandy loam)	Site 2 (silty clay loam)
Sand (%)	72	14
Silt (%)	19	56
Clay (%)	9	30
Bulk density (kg m ⁻³)	1360	1340
Electrical conductivity (dS m ⁻¹)	0.49	1.77
pH	6.7	7.7
Organic matter (g kg ⁻¹)	20	27

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557 **Figures caption**

558 Figure 1. Location maps in Brazil

559 Figure 2. Sketch of the experimental areas indicating the location of treatments Q1, Q2 and Q3
 560 (application of water with syphons with diameter 25.4, 38.1 and 50.8 mm, respectively), the
 561 location of the flumes, and the location of the secondary canal and drainage ditch

562 Figure 3. Example of furrow irrigation process on Site 1 (sandy loam), treatment Q1
 563 (application of water with syphons with diameter of 25.4, mm), irrigation I. (a) Advance and
 564 recession trajectories, (b) infiltration estimated along the furrow, and (c) inflow and outflow
 565 hydrographs and sediment concentration in the runoff water.

566 Figure 4. Average bed elevation along the furrows in Sites 1 and 2 (sandy loam and silty clay
 567 loam, respectively). The variability bars indicate plus and minus standard deviation.

568 Figure 5. Box plot chart representing the mean and variability of the inflow rated supplied by
 569 the syphons of diameter 25.4 mm (Q1), 38.1 mm (Q2) and 50.8 mm (Q3).

570 Figure 6. Mean advance time for each inflow treatment and irrigation event in (a) Site 1 (sandy
 571 loam) and (b) Site 2 (silty clay loam). The bars indicate plus-minus standard deviation among
 572 replication furrows.

573 Figure 7. Basic infiltration rate for every furrow in each treatment represented against the
 574 corresponding inflow rate, in (a) Site 1 (sandy loam) and (b) Site 2 (silty clay loam).

Figure 8. Soil loss vs. treatment mean inflow rate in Sites 1 and 2 (sandy loam and silty clay loam, respectively). The horizontal and vertical bars indicate plus-minus standard deviation among replication furrows.

Figure 9. Sediment loss vs. Distribution Uniformity and Application Efficiency for all furrows and irrigation events in treatments Q1, Q2 and Q3 (application of water with syphons with diameter 25.4, 38.1 and 50.8 mm, respectively) in (a) Site 1 (sandy loam) and (b) Site 2 (silty clay loam).

Figure 10. Sediment loss vs. Tail Water Ratio for all furrows and irrigation events in treatments Q1, Q2 and Q3 (application of water with syphons with diameter 25.4, 38.1 and 50.8 mm, respectively) in (a) Site 1 (sandy loam) and (b) Site 2 (silty clay loam).

Figure 1

Figure 2

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