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Effects of Cultivar and Irrigated Water Quality on Sugarcane Residue Decomposition

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In sugarcane cropping systems, green-cane harvesting has progressively replaced the traditional burning of standing crop prior to harvest, increasing the role of decomposition as a mechanism to replenish soil nutrients. We examined the impact of cultivar choice and irrigation water quality on decomposition of sugarcane residue. In two independent litterbag experiments, we isolated the effects of changes in plant residue quality and irrigated water quality. Cultivar residue exhibited significant variation of carbon and nitrogen concentrations and carbon to nitrogen ratio. Decomposition rate varied among cultivars, and those with greater carbon-to-nitrogen ratios decomposed faster than cultivars with lower ratios. Soil irrigated with river water showed a lower mineral and organic nitrogen concentration and decomposition rate than those irrigated with industry effluent wastewater. These results provide empirical evidence that both cultivar choice and water used for irrigation have a limited but significant impact on plant residue decomposition.

Keywords Litterbag experiment, litter chemistry, nutrient cycling

Introduction

Decomposition of plant residue is an important subprocess of mineral nutrient and carbon cycling in managed and natural terrestrial ecosystems (Swift, Heal, and Anderson 1979; Hobbie and Vitousek 2000). In natural ecosystems, decomposition largely regulates soil nutrient availability whereas in managed ecosystems, although nutrient input by fertilizers constitutes an important fraction of nutrient budget, the natural provision of nutrients through residue breakdown is also highly relevant because residue incorporation also ensures soil organic-matter formation and ameliorates water-holding capacity and nutrient availability (Reeves 1997; Greenwood et al. 2007). Because most agricultural systems constitute particularly open systems in terms of nutrient cycling, they often represent a potential threat for many natural surrounding ecosystems (Armour, Hateley, and Pitt 2009). Therefore, understanding the factors that control nutrient cycling will contribute to design more sustainable management practices.

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Sugarcane (*Saccharum officinarum* L.) production has experienced major technological changes that have tended to recycle and conserve a greater proportion of soil carbon (C) and mineral nutrients (Prove, Doogan, and Truong 1995; Robertson and Thorburn 2007). The green-cane harvesting system (mechanized harvesting) has been widely spread abroad, replacing the traditional burning prior to cane cutting, because it benefits ecosystem sustainability. This system reduces air pollution and soil erosion and increases water conservation with respect to burning technology (Wood 1991; Prove, Doogan, and Truong 1995; Kingston et al. 2005; Olivier and Singels 2007). Furthermore, there is evidence that depending on natural and management factors, green-cane harvesting enhances fertility, organic-matter contents, and biological activity of soils (Wood 1991; Sutton, Wood, and Saffigna 1996; Graham, Haynes, and Meyer 2002; Meier et al. 2006; Razafimbelo et al. 2006; Robertson and Thorburn 2007).

Plant litter decomposition rate depends on the combined action of climate, litter quality, and nutrient availability (Swift, Heal, and Anderson 1979; Melillo et al. 1982; Stott et al. 1986; Aber and Melillo 1991; Vitousek et al. 1994; Hobbie 1996). Environmental conditions (e.g., temperature and moisture) have a direct effect on residue decomposition because they help regulate soil microorganisms and their enzymatic activity (Swift, Heal, and Anderson 1979), and decomposition tends to increase with mean annual temperature and precipitation (Zhang et al. 2008). Residue quality plays a crucial role at different stages of residue decomposition (Taylor, Parkinson, and Parsons 1989; Briones and Ineson 1996; Hoorens, Aerts, and Stroetenga 2003; Tateno et al. 2007). In general, high initial lignin and low nitrogen (N) concentration negatively correlate with the rate of residue mass loss (Swift, Heal, and Anderson 1979; Aber and Melillo 1982; Melillo et al. 1982; Taylor, Parkinson, and Parsons 1989), although recent studies suggest that more complex combinations of nutrients would have a greater explanatory capacity than previous compounds such as lignin/N or C/N ratios (Zhang et al. 2008; Prescott 2010). Finally, exogenous N inputs are expected to accelerate decomposition, although empirical evidence is still controversial because N addition seems to stimulate residue decomposition of low-lignin substrates and reduce it in high-lignin ones due to a significant reduction of ligninolytic enzyme activity in the latter (Magill and Aber 1998; Carreiro et al. 2000; Knorr, Frey, and Curtis 2005).

Sugarcane production involves management decisions such as cultivar choice and the quality of water used for irrigation that may affect the decomposition dynamics of plant residue after harvest. Cultivar choice usually depends on specific ecophysiological features such as yield (Ferraro, Rivero, and Ghersa 2009), tolerance to soil salinity (Zérega, Hernández, and Valladares 1991; Akhtar et al. 2001; García and Medina 2003), response to fertilization (Chapman 1994; Vallis et al. 1996; Glaz et al. 2000), or disease resistance (Aday Diaz et al. 2003). Although different sugarcane cultivars seem to vary in the degree of detachment of their leaves after senescence (Cassalett, Viveros, and Amaya 1995; Thorburn, Meier, and Probert 2005), there is no evidence on the magnitude of the intraspecific variation of sugarcane residue quality and on the potential effects of such variation on residue decomposition dynamics, a phenomena relatively well studied for natural populations of other plant species (Madritch and Hunter 2005; Wimp et al. 2005; Semmartin, Garibaldi, and Chaneton 2008). For instance, predictive simulation models of sugarcane crops include a relatively less detailed submodel for soil and nutrient processes with respect to other ecophysiological features as they use a fixed average C/N ratio of the residue that decomposes in the soil (Probert et al. 1998; Lisson et al. 2005; Thorburn, Meier, and Probert 2005). Likewise, sugarcane crops may be irrigated with clear water from a natural source and with effluents derived from its industrialization process as well, which involves the addition of cellulose, simple sugars, fiber, and waxes together with water. These effluents influence crop performance and soil properties (Singandhupe et al. 2009, 2010), and they also might alter residue decomposition dynamics. However, empirical evidence is too limited to understand the impact on ecosystem functioning compared with other more widespread amendment techniques (Leal et al. 2010).

Here we examine to what extent variation in a few common agricultural practices (cultivar choice and irrigated water quality) impacts plant residue decomposition and several soil physicochemical features. We performed two independent litterbag experiments, under controlled conditions, to individually test the hypotheses that the intraspecific variation both in litter quality and in the irrigated water quality influence decomposition of sugarcane residue. We expect that (1) cultivars will display a certain degree of variation in residue quality (e.g., N, lignin, soluble compounds concentrations) that, in turn, will be translated into differences in decomposition rates, and (2) soils irrigated with industrial wastewater effluents will contain greater nutrient input and thus will enhance residue decomposition rates.

Materials and Methods

Study System and Experimental Design

We conducted two litterbag experiments, under controlled conditions, in the Faculty of Agronomy, University of Buenos Aires, during 2008, in which we incubated sugarcane harvest residue and soils provided by the Ledesma agribusiness corporation. This mill company encompasses more than 10% of the sugarcane cultivated area in Argentina, and we studied farms located in Libertador General San Martín, Province of Jujuy, in northwestern Argentina (23° 50′ 0″ lat.; S, 64° 45′ 50″ long W). Mean annual temperature in this subtropical region is 21 °C, and mean annual precipitation varies from 700 to 900 mm, concentrated in summer (December to March). Soil in this area is composed by a mosaic of three major types: sandy loam soils (udic Haplustalfs) in the low-landscape positions, silty loam soils (udic Argiustolls) on midslope and ridge-top landscape positions; and clay loam soils (typic Ustifluvents) on alluvial areas that occur close to the riverbanks in the flood plains (Ferraro, Rivero, and Ghersa 2009).

Farms belonging to Ledesma Corporation, as many others in the region, have progressively replaced the traditional burning prior to cane cutting by the green-cane harvesting and fulfill the crop water demand by flood irrigation (Ferraro, Rivero, and Ghersa 2009). Water used for irrigation may be directly pumped from the river or deep wells but also may be recycled from two industrial processes, pulp and paper mill production and sugarcane juice production. Paper water is collected at the end of the paper production chain and contains a considerable portion of the fine fibers and some fillers that are not retained through the screen wire for getting paper from pulp (Kannan and Oblisami 1990). The residual filter cake water, removed during the sugarcane juice clarification, is composed of sucrose, simple sugars, coagulated colloids, wax, sugarcane fiber, soil particles, and significant mineral elements (Rasul et al. 2006). In general, these farms are characterized by high levels of management intensity and high average sugarcane yields, greater than 85 t ha^{-1} (Ferraro, Rivero, and Ghersa 2009).

Experiment 1: Decomposition of Different Residues in a Common Soil. We performed a litterbag incubation experiment to evaluate the residue decomposition dynamics of four sugarcane cultivars that account for a large proportion of the cultivated area (Ferraro et al.

2009) (CP 70-1133, TUC 77-42, CP 72-2086, and NA 85-1602, hereafter named A, B, C, and D) in a common soil at 30, 60, and 90 days after incubation in a growth chamber. Residue was collected from four different production paddocks located in the farms previously described. To simulate the usual litter dynamics in the field all, cultivars were harvested in the same phenological stage, corresponding to physiological maturity. Residue corresponding to each of the four studied cultivars was collected in the three different plots located along each paddock and was mixed to generate one compound sample per cultivar.

Senescent sugarcane leaves and tops were cut into pieces of approximately 2 cm long to simulate the action of the soil macrofauna (Seastedt 1984). Single nylon bags (10 × 10 cm, 2-mm mesh) were filled with 1 g of each residue. Five litterbags corresponding to each cultivar and incubation period ($n = 5$) were randomly and individually placed on 750-cm^3 pots filled with a common soil that consisted in a mixture of soil and sand (50% each). We used a mixture of soil and sand that better adjusted to our device, designed to provide homogeneous and constant water provision to experimental units. Litterbags were covered with 1cm of this mixture and were softly pressed to enhance soil–residue contact. The 60 experimental units (pot + litterbag) were randomly assigned to a site within the growth chamber. Gravimetric water content of soil was kept constant by capillarity between 21% and 26% (representing ~75% of field capacity) by placing the pots on trays filled with foam porous blocks, containing a constant water table of 2 cm. Pots had a porous bottom to assure the capillarity with the foam blocks and to keep water supply constant. Water was supplied throughout the experiment by two 20-L Marriote siphons (a bottle equipped with a vertical inserted pipe, where the water pressure was equal to the atmospheric pressure) (Araki, Shiozawa, and Washitani 1998). Soil gravimetric moisture content in the pots was weekly evaluated.

In each harvest (30, 60, and 90 days), the corresponding five litterbags of each cultivar were removed from their respective pots and the content was rinsed thoroughly for 20 s, over a 2-mm mesh sieve to remove soil particles. Dry weight was determined after drying at 60 °C for 48 h. Five extra litter bags per cultivar type were treated as described but were immediately sent to the laboratory and their dry weight was used to adjust the initial litter mass for eventual manipulation losses.

Prior to incubations, we assigned 10 g of each residue and generated three samples to calculate the initial residue moisture content, and the concentration of the following indicators of residue quality: C, N, soluble celluloses (cellulose + hemicellulose), lignin, and C/N ratio. Total N and C were determined by dry combustion (LECO Corporation, St. Joseph, Mich.) and fiber estimation followed the technique proposed by Van Soest (1963, 1991).

Experiment 2: Decomposition of a Common Residue in Soils Irrigated with Different Water Quality. We performed a litterbag incubation experiment to determine the decomposition dynamics and a number of soil physicochemical features of a common sugarcane residue in originally similar soils from sugarcane plots that had been subjected to different irrigation water quality. In a greenhouse, we incubated residue from one of the cultivars used in experiment 1 (cultivar D). We chose cultivar D because it is one of the most used in the area (Ferraro, Rivero, and Ghersa 2009). We incubated litterbags in pots filled with soils collected in three production paddocks that have been irrigated with different water quality and regime: (1) water directly pumped from the river since 1998 (hereafter river water), water coming from the paper production process since 2004 (hereafter paper water), and water coming from the sugarcane juice clarification since 2003 (hereafter filter cake water).

Plots were located in midslope landscape positions and corresponded to loam soils. As in experiment 1, nylon bags (10 × 10 cm, 2-mm mesh) were filled with 1 g of residue of cultivar D. Five litterbags of each cultivar were harvested at days 30, 60, and 90 after incubation. Litterbags were placed in pots and incubated following the same procedure followed in experiment 1 and the experimental units (pot + litterbag) were randomly distributed.

We processed plant residue and soil as described for experiment 1, and we also measured the following soil parameters: pH, organic carbon, C/N ratio, and mineral N (ammonium and nitrate). Organic C and N contents were determined by dry combustion (LECO Corporation, St. Joseph, Mich.) on three samples per treatment, and soil mineral N [N-ammonium (NH_4^+) and N-nitrate (NO_3^-)] concentration was estimated by extracting and filtering five 5-g samples of soil with 25 mL of potassium chloride (KCl) 2 M followed by a colorimetrical determination (Alpkem Autoanalyzer, Ore.). For pH determinations, the five available samples had to be pooled and transformed in two samples.

Data Analysis

We analyzed residue mass remaining using two-way analyses of variance. In experiment 1, sources of variation were cultivar (four levels), incubation period (three levels), and their interaction, whereas in experiment 2, sources of variation were water quality (three levels), incubation period (three levels), and their interactions. Means were compared by Tukey's tests. We also estimated the residue decomposition constant (*k*) for both experiments as the slope of a single exponential model by regressing the log of the mass remaining against incubation time, the latter expressed as a proportion of the year (Swift, Heal, and Anderson 1979):

$$\ln (M_t/M_0) = b - kt$$

where M_0 is the initial dry mass and M_t is the dry mass remaining at time t. Replicates of *k* values for each treatment were generated to compare decompositions constant among treatments by bootstrap tests (Efron 1979) to have 125 *k* values for each treatment. Then we randomly selected 5 *k* values for each treatment and they were analyzed using one-way analysis of variance (ANOVA) followed by a Tukey test when corresponded. Residue quality (C, N, C/N, soluble cellulose and lignin) was analyzed using a multivariate analysis of variance (MANOVA) to evaluate possible differences among cultivars, followed by individual ANOVAs for each variable. We performed a linear regression of decomposition constant (*k*) against each single parameter. The effects of irrigated water quality on soil pH and mineral N were analyzed using individual ANOVAs for each variable. Means were compared by Tukey's tests. Finally, we performed a linear regression between decomposition constant and the evaluated soil variables (pH, mineral and total N, C, and C/N ratio).

Results

Decomposition of Different Residues in a Common Soil

Residue chemistry differed among cultivars (MANOVA, Wilks F = 6.63, $P = 0.003$). Variation was mainly accounted by N (F = 29.8; $P = 0.0001$), C/N ratio (F = 22; $P =$

Table 1

Initial residue quality characteristics of four sugarcane cultivars (A, CP 70-1133; B, TUC 77; C, CP 72-2086; D, NA 85-1602) (mean ±1 standard error, n = 3)

Cultivar	Carbon (%)	Nitrogen (%)	C/N	Soluble (%)	Cellulose (%)	Lignin (%)
A	44.9a ± 0.2	0.55b ± 0.03	81.7b ± 6.0	52.9a ± 0.8	39.5a ± 0.8	4.2a ± 0.3
B	44.7a ± 0.2	0.52ab ± 0.03	85.7bc ± 5.1	56.5a ± 2.3	33.3a ± 4.3	6.4a ± 2.4
C	44.6a ± 0.3	0.71c ± 0.03	62.5a ± 2.2	55.1a ± 0.7	28.9a ± 6.7	7.6a ± 3.3
D	45.8b ± 0.1	0.46a ± 0.03	98.7c ± 6.8	60.2a ± 0.7	32.1a ± 6.5	4.2a ± 1.3

Note. Different letters indicate significant differences among cultivars ($P < 0.05$).

0.0003), and C content (F = 16; $P = 0.0012$) (Table 1). Nitrogen concentration was greatest in cultivar C and lowest in D, and cultivar D had the greatest C content. The C/N ratio was greatest in cultivar D and lowest in cultivar C. In contrast, the different fractions of fiber did not significantly vary among cultivars ($P > 0.2$, Table 1).

After 90 days of incubation, approximately 60% of the initial residue mass was decomposed ($F_{2,48} = 119$; $P < 0.0001$, Figure 1 left panel). Residue decomposition constant of cultivar D was significantly greater than those of cultivars B and C ($F_{3,16} = 6$; $P = 0.006$, Figure 1 right panel). Residue decomposition constants positively correlated with C/N ratio (Figure 2).

Decomposition of a Common Litter in Soils Coming from Different Irrigated Water Quality

Soils irrigated with paper and filter cake water had a significant greater N content than soil irrigated with river water ($F_{2,3} = 20.1$; $P = 0.01$; Figure 3). Instead, soil C content ($F_{2,3} = 4.41$; $P = 0.1$) and C/N ratio ($F_{2,3} = 1.28$; $P = 0.3$) did not vary among soils (Figure 3). Mineral N contents of soils irrigated with water from paper production had greater contents

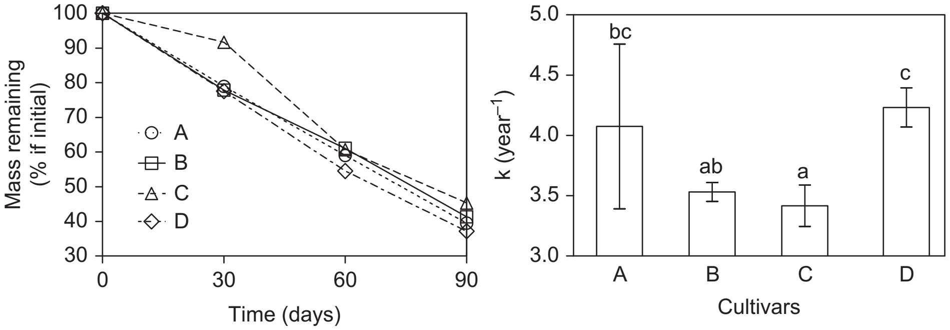

Figure 1. Left panel: Decomposition dynamics of residue mass loss of four sugarcane cultivars (A, CP 70-1133; B, TUC 77; C, CP 72-2086; and D, NA 85-1602) over 90 days of incubation (error bars are omitted for clarity, n = 5). Right panel: Decomposition constant (*k*) of the same four sugarcane cultivar residues. Bars are means for each cultivar (n = 5); vertical bars indicate ±1 standard error. Different letters denote mean significant differences among residual decomposition constant from an ANOVA test.

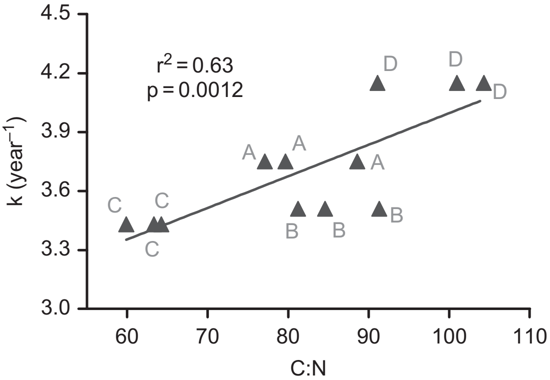

Figure 2. Relationship between initial C/N ratio of residue and decomposition constant (*k*) of sugarcane residue corresponding to four cultivars (A, CP 70-1133; B, TUC 77; C, CP 72-2086; and D, NA 85-1602). Each point represents the combination of each C/N replicate (n = 3) with a mean k value calculated from the five replicates randomly generated by the bootstrap technique (see methods). The line corresponds to the best-fit line.

than soils irrigated with water pumped from river ($F_{2,12} = 5.94$; $P = 0.01$, Figure 4), and soil pH did not vary among soils ($F_{2,3} = 1.53$; $P = 0.3$, Figure 4).

After 90 days of incubation, approximately 30% of initial litter mass was decomposed ($F_{2,36} = 18.36$; $P = 0.0001$, Figure 5 left panel). Residue decomposition in soils irrigated with river water was less than that in soils irrigated with paper and filter cake water ($F_{2,36} = 7.32$; $P = 0.002$, Figure 5 left panel). This difference was marginally detected when we compared the decomposition constants ($F_{2,12} = 2.9$; $P = 0.09$, Figure 5 left panel). We did not find a significant correlation among decomposition constant and the measured soil variables (P values > 0.05).

Discussion

Our results showed that management decisions such as sugarcane cultivar and the irrigated water quality might potentially affect variables related to C and N cycling during residue decomposition. The first experiment showed that cultivars that are sufficiently similar as to be used in a specific geographical area differed more than 50% in the C/N ratio and N concentration of their residue. In turn, this variation was associated to moderate but significant differences in decomposition rates, although it occurred in an opposite pattern than expected because cultivars with higher C/N ratio decomposed faster than those with lower C/N ratio. The second experiment showed that soils irrigated with water from sugarcane industry effluents had more mineral and organic N and had a slightly greater decomposition than soil irrigated with clear water directly pumped from river.

The intraspecific variation of plant litter quality and its impact on other ecosystems components or processes have been relatively well studied in grasslands and forests but have received little attention in agricultural ecosystems (Griffiths et al. 1992; Bardgett and McAlister 1999; Saetre and Bååth 2000). To our knowledge, this is the first study that investigated the magnitude of sugarcane intraspecific variation of residue quality and its potential influence on its decomposition dynamics. Current mechanistic, process-based simulations models of crops in general, and of sugarcane in particular, include soil submodels that explicitly consider residue decomposition, but users seem to simplify the role

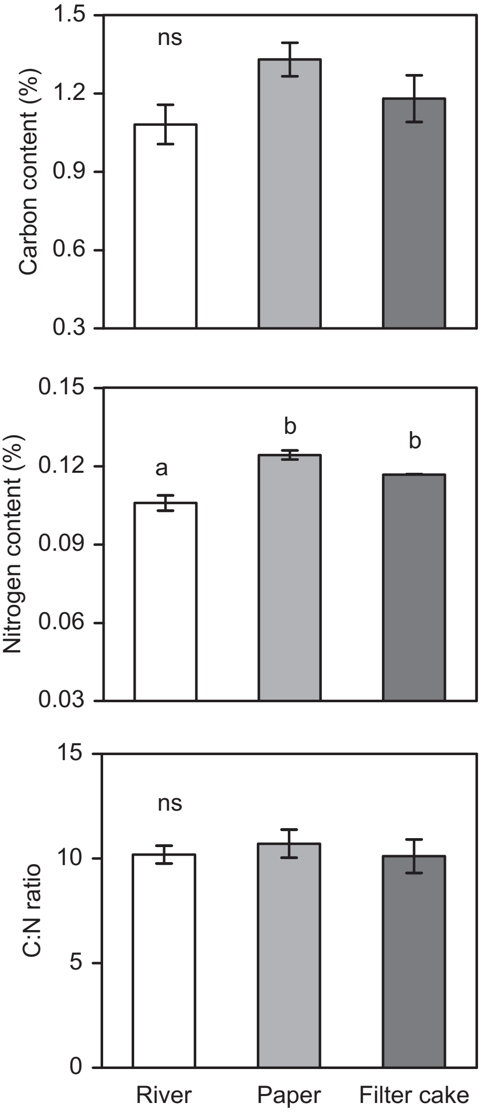

Figure 3. Carbon and N contents and C/N ratio of soils subjected to irrigation with waters of different qualities: river (clear water directly pumped from river), paper (residual water from pulp and paper production), and filter cake (residual water from sugarcane juice clarification). Bars are means for each treatment (n = 3). Different letters denote significant differences ($P < 0.05$). Vertical lines indicate ±1 standard error.

of litter quality on this process and set general C/N fixed ratios usually recommended for specific crops (e.g., 80–110 for sugarcane) (Probert et al. 1998; Lisson et al. 2005; Galdos et al. 2010). Our results showed that four cultivars used in a relatively circumscribed area displayed up to 50% of variation of the C/N ratio (62 to 98). Although we found only moderate variation of cultivar decomposition dynamics, we believe that it is necessary to 265 expand our understanding on this issue, to evaluate its net influence under field conditions, and eventually to effectively incorporate it in modeling.

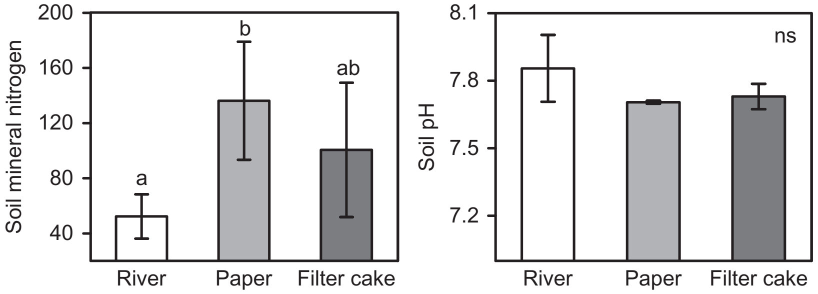

Figure 4. Soil mineral N (ammonium + nitrate) and soil pH of soils subjected to irrigation with waters of different qualities: river (clear water directly pumped from river), paper (residual water from pulp and paper production), and filter cake (residual water from sugarcane juice clarification). Bars are means for each treatment (mineral N n = 5; pH n = 2). Different letters denote significant differences between treatments ($P < 0.05$). Vertical lines indicate ±1 standard error.

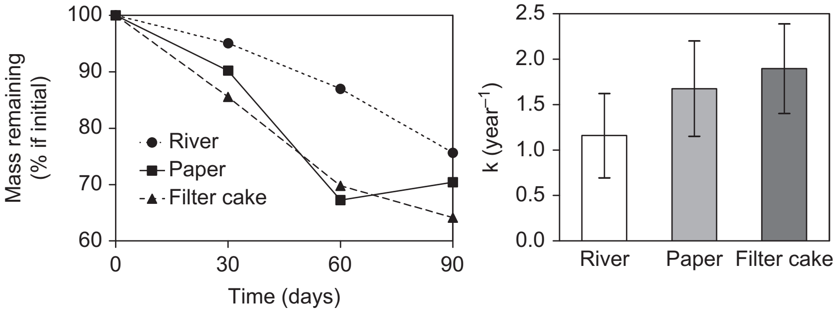

Figure 5. Left panel: Decomposition dynamics of residue mass loss of a single sugarcane cultivar (D) over 90 days of incubation in soils subjected to irrigation with waters of different qualities: river (clear water directly pumped from river), paper (residual water from pulp and paper production), and filter cake (residual water from sugarcane juice clarification) (error bars are omitted for clarity, n = 5). Right panel: Decomposition constant (*k*) of a single sugarcane cultivar (D) in soils subjected to irrigation with water of different quality (categories as in left panel). Values are means for each treatment (n = 5). Vertical lines indicate ±1 standard error.

Initial C/N ratio of aerial plant litter has traditionally been considered as one of the components that best predict litter decomposition rate (Aber and Melillo 1982; Melillo et al. 1982). As a rule, greater C/N ratios and other traits such as lignin/N ratio reduce litter decomposability (Melillo et al. 1982; Enriquez, Duarte, and Sand-Jensen 1993). A recent global analysis from field litterbag experiments indicated that the single C/N ratio throughout a gradient from 20 to 100 was negatively correlated with litter decomposition (Zhang et al. 2008). Nevertheless, C/N explained a small fraction of variance (3%) and, for instance, for a given C/N ratio it is possible to find a 10-fold variation in litter decomposition rate (Zhang et al. 2008). Instead, the same analysis showed that when C/N ratio is combined with the sum of other nutrients such as N, P, calcium, potassium, and manganese, the explanative power is raised to about 70%, suggesting that other nutrients interact with C and N of plant residue and influence decomposition (Zhang et al. 2008). Although our results do not coincide with the predictions derived from the most accepted models, we are aware that cultivar D, the one with greater decomposition rate, had greater

C/N ratios but it also had the greatest (nonstatistically significant) soluble contents and relatively low lignin contents, which might contribute to explain the greater residue decomposition. In any case, our results, in agreement with a number of studies that did not find a clear correlation among litter C/N fraction and decomposition rate (Kaneko and Salamanca 1999; Martinez-Yrìzar, Núñez, and Búrquez 2007), suggest that this model deserves more fine-tuning.

The utilization of effluents from sugarcane industrialization for irrigation may be beneficial in terms of water and nutrients conservation and as a strategy to reduce pollution in aquatic habitats surrounding farmlands (Armour, Hateley, and Pitt 2009; Leal et al. 2010). Nevertheless, empirical evidence of their impact on soil properties and nutrient cycling is scarce. In coincidence with a previous study in eastern India, where effluents addition increased sugarcane production and soil nutrients (Singandhupe et al. 2009), our results showed a positive effect on organic and mineral soil N. We also found significantly greater residue decomposition in soils irrigated with residual water but we did not find a significant relationship among decomposition and soil N content, a still controversial issue (Knorr, Frey, and Curtis 2005; Prescott 2010). In this regard, results from empirical studies on the impact of N supply to plant litter decomposition show, on the one hand, faster decay rates in response to increased external N availability (Hunt et al. 1988; Hobbie and Vitousek 2000). On the other hand, several studies have reported either no significant (McClaugherty and Berg 1987; Pastor, Stillwell, and Tilman 1987; Hunt et al. 1988; Prescott 1995; Hobbie and Vitousek 2000) or slight effects, depending on fertilization rates, ambient N deposition, and residue quality (Knorr, Frey, and Curtis 2005). The use of this type of water (N loaded) and N addition as fertilizer should be adjusted to crop requirements to avoid environmental pollution by losses to groundwater and to the atmosphere (Armour, Hateley, and Pitt 2009). Further research under field conditions will be central to determine to what extent irrigation with sugarcane effluents improves crop productivity and reduces pollution. An explicit consideration of these factors would broaden the understanding of C and nutrient cycling in agroecosystems, enhance the accuracy of predictive models, and prevent environmental pollution.

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