Rototillage, Disking, and Subsequent Irrigation: Effects on Soil Nitrogen Dynamics, Microbial Biomass, and Carbon Dioxide Efflux

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ABSTRACT

Spring and summer tillage are usually followed by irrigation before planting crops in California's summer-dry Mediterranean-type climate. Tillage treatments such as rototillage or disking are known to disturb the soil structure to different extents, but little is known about how the intensity of a tillage event and subsequent irrigation affect the microbial biomass, respiration, CO_2 efflux, and mineral N of agricultural soils. We carried out an experiment with a Yolo silt loam (fine-silty, mixed, superactive, nonacid, thermic Mollic Xerofluvent) with two tilled treatments (rototillage and disked and rolled) and a nontilled control. The soil was subsequently sampled throughout a 17-d period. Nine days after tillage, all treatments were lightly sprinkler-irrigated to bring the soil water potential above −10 kPa. After tillage, the soil ammonium and nitrate content increased rapidly relative to the control with highest increases in the disked soil. Mineral N remained higher in the tilled treatments after irrigation. Rototillage and disking increased the CO_2 efflux of the soil within 24 h of the disturbance. The increase was higher in the disked soil, which was more than three times the CO_2 efflux of the control soil at 0.25 h after tillage. This effect may be due to degassing of dissolved CO_2 since microbial respiration did not increase in tilled soils. Irrigation increased the CO_2 efflux of all treatments but this was most pronounced in the control soil, which had an order of magnitude increase in CO_2 efflux after irrigation. An ancillary experiment carried out under similar conditions but with more frequent sampling showed that increases in CO_2 efflux after irrigation were accompanied by increases in soil respiration. This study shows that different tillage implements affect CO_2 efflux, nitrate accumulation, and microbial activity, and thus have different effects on soil and atmospheric environmental quality.

Tillage causes short-term changes in soil biology and nutrient dynamics. Tillage can alter the microbial community structure of the soil within days of disturbance (Calderón et al., 2001). Tillage can lead to C loss from agricultural soils because of the exposure and subsequent oxidation of previously protected organic matter (Reicosky et al., 1995). Tillage can also initiate increases in soil mineral N content and denitrification within hours after the disturbance (Reicosky et al., 1997; Calderón et al., 2000, 2001).

Carbon dioxide efflux is a physical process defined as the flow of CO_2 from the soil toward the atmosphere, and it is measured at the soil surface (Rolston, 1986). Tillage can be followed by a short-term burst of CO_2 efflux to the atmosphere, explained in part by the physical degassing of dissolved CO_2 from the soil solution (Reicosky and Lindstrom, 1993; Reicosky et al., 1995, 1997; Kessavalou et al., 1998; Rochette and Angers, 1999; Ellert and Janzen, 1999; Calderón et al., 2001). Microbial stress after tillage may lead to decreases in soil respiration, that is, the biological production of CO_2 by organisms in the soil (Anderson, 1982), even when high soil CO_2 efflux occurs (Calderón et al., 2001).

Different tillage implements vary in the intensity of soil disturbance. At one end of the spectrum are the rototillers, which have powered blades that disrupt aggregates intensely, whereas nonpowered disk mechanisms may be effective at inverting the soil profile but cause less aggregate breakdown (Larney and Bullock, 1994). Moldboard-plowed soils have high surface roughness, large soil surface area, and a large void fraction relative to disk-harrowed soils. Because of this, moldboard plowing causes a short-lived but very high CO_2 efflux (Reicosky and Lindstrom, 1993). The depth of the disturbance and the size of the voids (which permit air diffusion into the soil) are important factors in determining the efflux response to tillage (Reicosky and Lindstrom, 1993).

Tillage may be followed by significant increases in water vapor flux, which result in the drying of soil (Kessavalou et al., 1998). For this reason, tillage is often followed by irrigation to provide sufficient moisture for seed germination. Rewetting of dry soil stimulates C and N mineralization from microbial and organic sources (Sparling and Ross, 1988; van Gestel et al., 1993), but there is little data on how irrigation of recently tilled soils affects soil nitrogen dynamics and gas fluxes. This knowledge gap may be important, because soil wetting can be followed by short-lived bursts in greenhouse gas production (Kessavalou et al., 1998), and tillage may stimulate nitrate production, increasing the potential for nitrate leaching and denitrification losses.

Our hypothesis is that use of different types of tillage implements will affect CO_2 efflux and net N mineralization of nitrogen after tillage. Based on previous studies (Calderón et al., 2000, 2001), microbial biomass and respiration are not expected to increase immediately after tillage, but increased net N mineralization and nitrate availability may occur. While the effect of tillage on soil CO_2 efflux is expected to be due to physical processes, we hypothesize that irrigation may increase microbial activity and respiration (Lundquist et al., 1999), and this will contribute to the CO_2 efflux of recently tilled soils after rewetting. We tested these hypotheses in a short-term field experiment in an agricultural field in California with three treatments: rototilled soil, disked and rolled soil, and a nontilled control.

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Abbreviations: DON, dissolved organic nitrogen; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen.

MATERIALS AND METHODS

The experimental site was at the University of California, Davis in the Central Valley of California. The soil was a Yolo silt loam left fallow from the fall of 1998 until the start of the experiment in May 1999. The plot was a 14- by 24-m rectangle that ran east to west lengthwise. We kept the plot weed-free through the winter by the application of Roundup herbicide (Monsanto, St. Louis, MO) as well as clipping of seedlings with care not to disturb the soil. At the start of the experiment, less than 4 g dry weight m^{-2} of weeds were present, so the soil was essentially bare during rototillage or disking.

Soil Characteristics Measured Before the Experiment

Five months before the experiment, we obtained three composite soil samples at the 0- to 15-cm depth from a east–west transect along the center of the field at three evenly spaced points. We analyzed the samples for pH, cation exchange capacity, texture, organic matter content, organic C, and organic N (Table 1).

To determine the soil moisture characteristic curve of the Yolo silt loam, intact cores were obtained immediately inside each of the four corners of the field. Polyvinyl chloride pipes (30.5 cm deep and 12.7 cm in diameter) were pounded into the soil and were subsequently dug up with care not to disturb the soil. In the lab, we placed a tensiometer in each core and added water until each soil core reached field capacity. We took simultaneous tensiometer readings and gravimetric moisture as the soil dried to calculate the relationship between water content and water potential.

Tillage

For rototillage, we used a Kubota (Osaka, Japan) FL 850 rototiller pulled by a Kubota B6200 tractor. The disk implement was a Strathmore Machinery (Strathmore, CA) Model 6 with two rows of eight disks each. A Schmeiser (Fresno, CA) roller was attached to the disk implement.

One day before the experiment, we carried out a trial of the rototiller and the disk implements in an area immediately outside of the experimental plot. Adjacent transects of soil (10 m long) were rototilled or disked to determine the effect of the implements on the soil bulk density, as well as the depth and width of the rototilled and disked soil layers. In order to determine the bulk density of the tilled and control soils, we obtained duplicate soil cores from the rototilled, disked, and adjacent intact soil by driving polyvinyl chloride pipes (13.2 cm in diameter) into the soil and digging them out with care not to disturb the soil. The top 15 cm of soil from each core was dried for 24 h at 105°C and the dry bulk density was calculated as grams dry soil per cm^3.

Experimental Design

For the main experiment, three treatments (rototilled, disk, and a nontilled control) were replicated three times in three adjacent complete blocks. Each of the blocks was 4.6 by 24 m. There were a total of nine treatment–block combinations. Tillage occurred on 25 May 1999, and took less than 20 min. The start of tillage was taken as time zero. At 9 d after tillage (222 h), we irrigated for 0.5 h with a sprinkler system. The sprinklers were placed regularly along the edges of the three blocks to achieve an even distribution of the irrigation water throughout the experimental plot. Irrigation increased the soil moisture at the 0- to 15-cm depth from a range of 109 to 137 g H_2O kg^{-1} dry soil (−20.1 to −50.1 kPa) to a range of 156 to 176 g H_2O kg^{-1} dry soil (−0.1 to −8.8 kPa). The observation that the moisture front did not reach below 15 cm in the control and rototilled soil suggests that there was no significant leaching after irrigation in these treatments. Some irrigation water reached below 15 cm in the disked treatment, probably due to the presence of large voids in the soil.

Table 1. Characteristics of the Yolo silt loam soil. The soils were sampled 5 mo before the experiment at the 0- to 15-cm depth and sieved so that only the <2-mm fraction was analyzed. Data are the mean (standard error), $n = 3$.

Variable	Mean (standard error)	Method
pH	6.5 (0.3)	saturated paste
Cation exchange capacity, $cmol_c$ kg^{-1} dry soil	25.6 (1.5)	Janitzky (1986)
Sand, %	37 (0.6)	Gee and Bauder (1986)
Silt, %	47 (0.0)	Gee and Bauder (1986)
Clay, %	16 (0.6)	Gee and Bauder (1986)
Organic matter, g kg^{-1}	8.8 (0.2)	Pella (1990)
Organic carbon, g kg^{-1}	7.3 (0.1)	Pella (1990)
Organic nitrogen, g kg^{-1}	0.95 (0.01)	Pella (1990)

We took soil cores at randomly preselected sites along transects that spanned the length of the treatment strips. Cores were composited from these sites to make nine samples, each from one of the treatment–block combinations. We sampled for all the variables at the following times after tillage: 0.3, 12, 24.5, 72, 168, 240, 312, and 408 h. In addition to these eight samplings, we took extra samples for CO_2 efflux at 6, 48, 96, 223, and 264 h after tillage.

At each sampling time, we obtained 0- to 15-cm-deep soil samples with a bucket auger (6.7 cm in diameter). Samples at 0 to 3 cm were only taken on the last sampling time at 408 h after tillage. The soils were placed in a cooler and transported to the laboratory, where we mixed the soil by hand, and completed sample preparation in less than one hour.

For all measurements in this study, we used the 0- to 15-cm depth increment of the Ap horizon because this approximates the depth of tillage (see below). The data are expressed as concentrations, which are useful for comparisons of microbial activity, rather than equivalent mass measurements, which are more appropriate for showing the role of soils as a reservoir for nutrients at an ecosystem level (Ellert and Bettany, 1995).

Measurements

For extractable mineral nitrogen, three samples (10 g moist soil) were taken from each treatment–block combination. Each sample was mixed with 25 mL of 2 *M* KCl, shaken for 20 min, and centrifuged, and the supernatant was stored at −20°C until analysis. The concentration of ammonium and nitrate in the soil extracts was determined using a Lachat Quick Chem II Flow Injection Analyzer (Zellweger Analytical, Milwaukee, WI). Gravimetric moisture was determined after drying approximately 50 g of soil at 105°C for 48 h.

At each sampling time, one sample from each treatment–block combination was analyzed for microbial biomass carbon (MBC) and nitrogen (MBN) using the fumigation–extraction method (Brookes et al., 1985; Vance et al., 1987). We added 60 mL of 0.5 *M* K_2SO_4 to 25 g of fresh soil. The mixture was shaken for 30 min and filtered (Whatman [Maidstone, UK] #40). Another soil sample from the same treatment was fumigated for 24 h with purified chloroform ($CHCl_3$). After the fumigation, the soil was extracted in the same way as the fresh soil. Aliquots of the fumigated and fresh soil extracts were oxidized with dichromate in concentrated sulfuric–phosphoric acid, and the residual dichromate was determined by titration with ferrous ammonium sulfate (Vance et al., 1987; Yeomans and Bremner, 1988). We calculated the MBC by multiplying

the additional C in the fumigated samples by 2.64 (Vance et al., 1987). For MBN, aliquots of the same extracts used for the MBC were subjected to Kjeldahl digestion (Wyland et al., 1994). The total ammonium in the digests was analyzed with a Lachat Quick Chem II Flow Injection Analyzer (Zellweger Analytical). We calculated the total MBN by multiplying the flush of inorganic plus organic N by 1.86 (Brookes et al., 1985). The dissolved organic nitrogen (DON) was obtained by using the amount of organic N in the fresh soil extracts; the 0.5 *M* K_2SO_4 extract of fresh soils contains many forms of organic N that may potentially be available for microbial utilization (Badalucco et al., 1992).

For soil respiration, two subsamples from each treatment combination were analyzed. We placed 200 g of moist soil in a 250-mL jar. Each jar was then sealed with a gas-tight screw cap fitted with a septum for gas sampling, then incubated at 25°C for 1 h. After the incubation, the jars were shaken gently by hand and the headspace was sampled with a syringe. Carbon dioxide in the headspace samples was analyzed with an infrared gas analyzer (Horiba [Riverside, CA] PIR-200). The amount of CO_2 was calculated by comparison with a known CO_2 standard.

We obtained two samples of CO_2 efflux from every treatment–block combination using the closed chamber method modified from Rolston (1986). The gas sampling chambers consisted of a bottom ring and a cap. Two rings made of thin-walled polyvinyl chloride (13.2 cm in diameter, 10 cm high) were placed close to the center of each treatment–block subplot. Each ring was pushed approximately 5 cm into the soil immediately after the tillage and left in place for the duration of the experiment. The caps were constructed from thin-walled polyvinyl chloride pipe (13.2 cm in diameter, 5 cm high) with a Plexiglas top glued to one end. The caps were fitted for gas sampling and had a small aperture to the outside to allow for equilibration with ambient pressure. To measure the gas fluxes, we taped the caps to the bottom rings at time zero, then took 3-mL headspace samples at 15 and 30 min after cap placement. The samples were taken immediately to the laboratory and analyzed using an infrared gas analyzer (Horiba PIR-200). A mixture of 0.1% CO_2 in air was used as a standard. After the last sampling of the experiment, we measured the distance between the soil surface and the top of each ring in order to estimate the internal volume of the chambers above the level of the soil. This data, together with the CO_2 concentration, was used to calculate the CO_2 efflux. We measured the soil temperature (7.5 cm deep) adjacent to the bottom rings concurrently with the efflux measurements. Most samplings were carried out between 0600 and 0800 hours. The average soil temperatures for these morning measurements were 18.4°C for the control soil, 17.7°C for the rototilled soil, and 17.3°C for the disked soil. The samplings at 6, 12, 96, and 223 h were carried out in the afternoon hours and the average soil temperatures were 25°C for the control soil, 24.6°C for the rototilled soil, and 24.4°C for the disked soil.

An ancillary experiment examined the effect of irrigation on soil respiration and efflux dynamics at a finer time scale. Soil respiration, CO_2 efflux, soil temperature, and soil moisture were measured. The experiment was carried out in a 4- by 4-m area located 5 m away from the main experiment. The plot consisted of three strip treatments: a 1.7-m-wide disked and rolled strip, a 1-m-wide rototilled strip, and a 1.7-m-wide nontilled strip. Four caps for efflux sampling were placed in each tillage treatment on a transect perpendicular to the tillage strips. The soil had been tilled 15 d before the irrigation. The strips were watered uniformly with distilled water using a portable sprayer. The watering lasted for 30 min and delivered enough water to moisten the top 15 cm of soil to a range of 139 to 146 g H_2O kg^{-1} dry soil (−13.2 to −18.5 kPa), which was slightly drier than the moisture of the recently irrigated soil in the main experiment. The soil samplings were carried out 1 h before watering and 0.8, 2.4, 5.8, and 17.7 h after watering. Soil samples (0–15 cm) for respiration and moisture were obtained from preselected random sites in the same manner as the main experiment.

Statistical Analyses

The main experiment was analyzed statistically as a complete block design. We conducted a three-way analysis of variance with the GLM procedure of SAS Version 6.11 to test effects of tillage treatment, time, and block (SAS Institute, 1999). Mean separations were with the least significant difference (LSD) test. For the ancillary experiment, *t* tests were used for mean comparisons.

RESULTS

Main Experiment

Tillage caused reductions in the bulk density of the disked and rototilled soil (data not shown). The dry bulk density of the undisturbed control soil was 1.4 g cm^{-3}. The disked soil bulk density decreased to 1.0 g cm^{-3}, while the rototilled soil fell to 0.9 g cm^{-3}. The depth of the disturbed soil layer for the disked and rototilled soils ranged from 14 to 16 cm.

The moisture content of the soils from the three treatments was similar at time zero (Fig. 1). There was no measurable precipitation between the time of tillage and irrigation, so all the soils dried gradually. After tillage, the disked soil lost moisture more rapidly than the control soil (Fig. 1). The rototilled soil lost the least amount of moisture with less than a 15% reduction in moisture during the first 168 h after tillage. By this time, there were significant moisture differences between the treatments (Table 2). Irrigation temporarily increased the soil water content of the 0- to 15-cm layer by 22 to 47% of the pre-irrigation amounts. The soils dried gradually after irrigation due to the lack of precipitation, but the disked soil remained at lower moisture than the other two treatments.

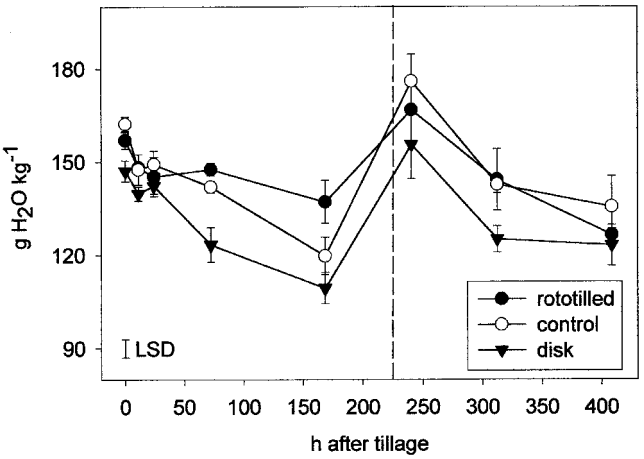

Fig. 1. Mean gravimetric moisture content of the rototilled, disked, and control soils in the main experiment. The soils were tilled at 0 h. The time of irrigation (222 h) is indicated by the vertical dashed line. For reference, 110 g H_2O kg^{-1} is equivalent to −50 kPa. The error bars are the standard error of the mean (n = 3).

Table 2. Results of the analysis of variance (ANOVA) of the disked, rototilled, and control soils.

Variable	Time	Tillage	Time × tillage
Ammonium, mg NH^+_4–N kg^{-1}	*	*	NS†
CO_2 efflux, mg CO_2 m^{-2} h^{-1}	*	*	*
Dissolved organic nitrogen (DON), mg kg^{-1}	*	*	NS
Microbial biomass carbon (MBC), mg kg^{-1}	NS	NS	NS
Microbial biomass nitrogen (MBN), mg kg^{-1}	*	NS	NS
Moisture, g H_2O kg^{-1}	*	*	NS
Nitrate, mg NO^-_3-N kg^{-1}	*	*	NS
Respiration, μg CO_2 kg^{-1} h^{-1}	*	NS	NS

* Significant at the 0.05 probability level.
† Not significant.

The ammonium concentration in all treatments remained below 2 mg N kg^{-1} dry soil (Fig. 2a). However, ammonium increased significantly in both the rototilled and disked treatments relative to the control ($P < 0.05$; Table 2), and remained high for the duration of the experiment, even after irrigation. Toward the end of the experiment, ammonium concentration in the rototilled soil was twice that of the control, while the disked soils had an ammonium concentration three times higher than the control (Fig. 2a).

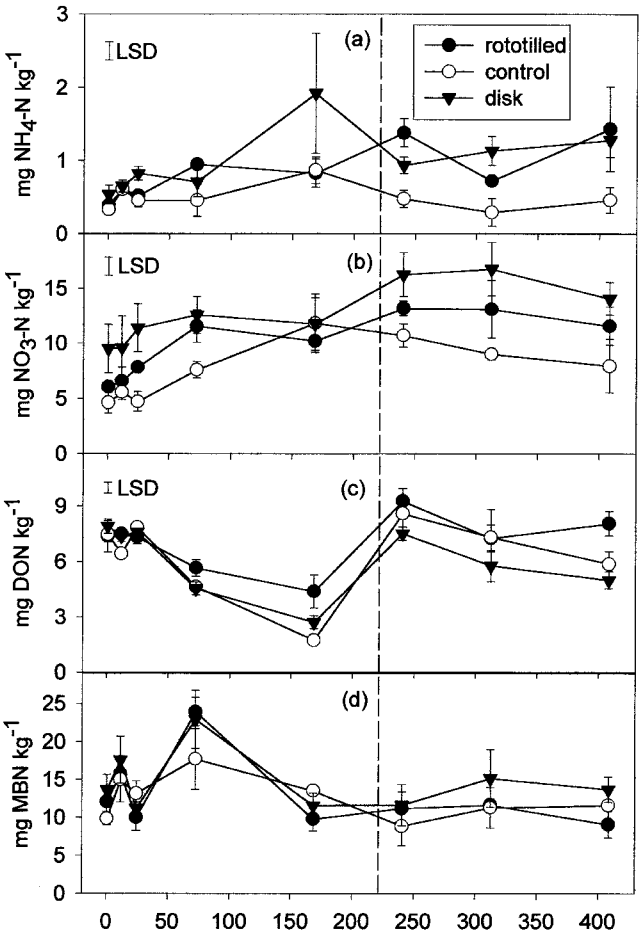

Fig. 2. Mean values for the nitrogen pools of the rototilled, disked, and control soils. (*a*) NH_4–N, (*b*) NO_3–N, (*c*) dissolved organic nitrogen (DON), and (*d*) microbial biomass nitrogen (MBN). The soils were tilled at 0 h. The time of irrigation (222 h) is indicated by the vertical dashed line. The error bars are the standard error of the mean ($n = 3$). There were no significant differences in MBN at any time.

Tillage was followed by significant increases in nitrate in the disked and the rototilled soils compared with the control (Fig. 2b, Table 2). At 24 and 72 h, the rototilled and disked soils had higher nitrate concentration than the control. However, at 168 h after tillage, all treatments had statistically indistinguishable nitrate concentrations because the control soil showed a gradual increase in nitrate after time zero, reaching more than twice the original concentration at 168 h. This change in nitrate concentration in the control soil was concurrent with a decrease in soil moisture (Fig. 1). After irrigation, nitrate increased by 42% in the disked soil and 29% in the rototilled soil, reestablishing the initial differences that occurred between the treatments after tillage (Fig. 2b).

Dissolved organic N decreased in all treatments, and was 40 to 50% lower after 168 h compared with the onset of the experiment (Fig. 2c). The decline in DON was less marked in the rototilled soil. The DON increased in all treatments following irrigation. The control soil had the highest response of DON to irrigation, with nearly a fivefold increase from before irrigation to immediately after.

Microbial biomass N of the 0- to 15-cm layer was statistically similar among all treatments throughout the experiment (Fig. 2d, Table 2). The 0- to 3-cm depth, which was sampled at the end of the experiment, showed that MBN was more greatly reduced by rototillage compared with the other two treatments (Table 3).

There were no significant differences between treatments in the MBC taken at the 0- to 15-cm depth at any point during the experiment (Fig. 3a, Table 2), although temporal fluctuations occurred throughout the experiment. After 17 d, however, the MBC of the 0- to 3-cm depth was reduced in the rototilled and the disked soils as compared with the control soil (Table 3).

Soil respiration remained statistically indistinguishable between the tilled treatments and the control throughout the experiment (Fig. 3b, Table 2). It ranged

Table 3. Microbial biomass carbon (MBC) and nitrogen (MBN) from the 0- to 3-cm depth of soils sampled at block one 408 h after the start of the experiment. Means within a column followed by different letters are significantly different based on a *t* test ($P < 0.05$). Data are the mean (standard error), $n = 3$.

Treatment	MBC	MBN
	mg C kg^{-1}	mg N kg^{-1}
Control	249.8 (54.9)a	12.78 (2.35)a
Disked	147.0 (16.3)b	11.49 (2.54)a
Rototilled	57.4 (44.3)c	1.58 (0.81)b

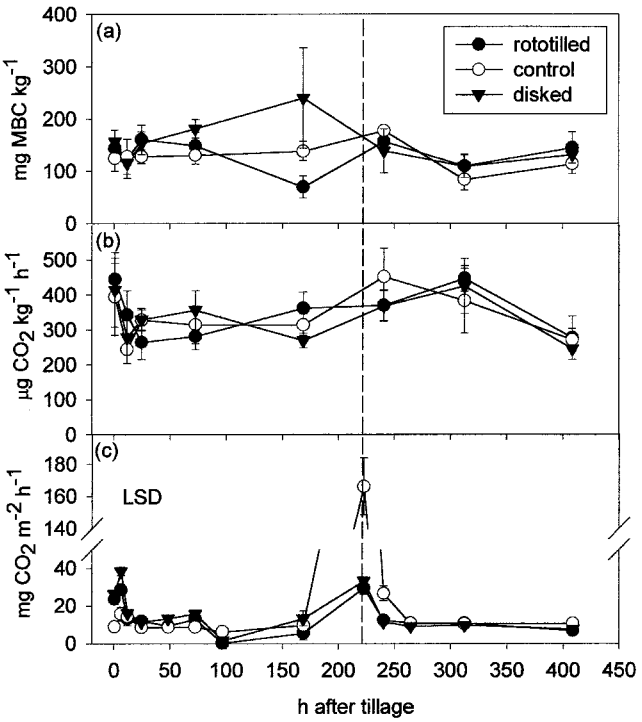

Fig. 3. Mean values for the microbial biomass carbon, respiration, and CO_2 efflux of the rototilled, disked, and control soils. (*a*) Microbial biomass carbon (MBC), (*b*) respiration, and (*c*) CO_2 efflux. The soils were tilled at 0 h. The time of irrigation (222 h) is indicated by the vertical dashed line. The error bars are the standard error of the mean (n = 3). The least significant difference (LSD) between the treatments is shown. There were no significant differences in MBC or respiration at any point during the experiment.

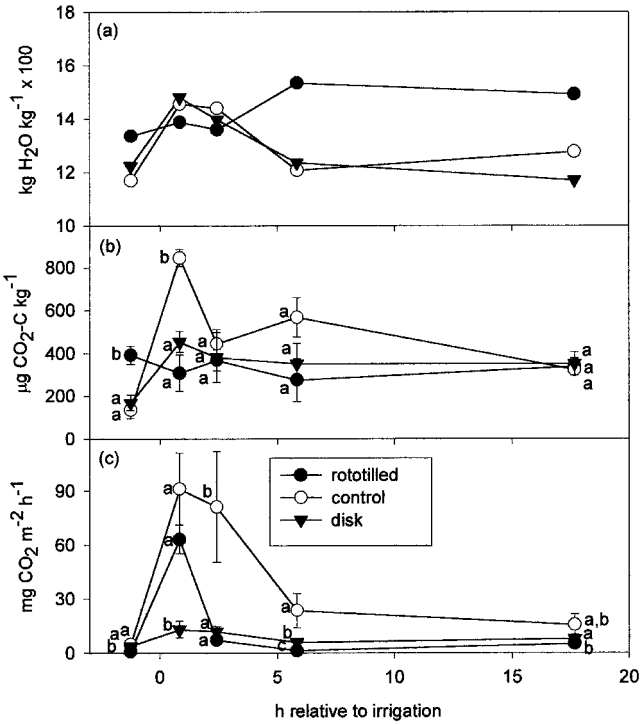

Fig. 4. Mean gravimetric moisture content, respiration, and CO_2 efflux of the rototilled, disked, and control soils in the ancillary experiment. (*a*) Gravimetric moisture, (*b*) respiration, and (*c*) CO_2 efflux. The soils were irrigated at 0 h. The error bars are the standard error of the mean (n = 3). Different letters indicate significant differences ($P < 0.05$) using t tests between treatments at each time. No t tests were done for the moisture data since only one replicate per treatment combination was analyzed.

from 245 to 452 μg CO_2–C kg^{-1} dry soil h^{-1}. The significant time effect occurred because the respiration of all three treatments increased 40 to 60% just after irrigation. In the main experiment, however, we did not obtain respiration data until 12 h after irrigation, so we carried out a more detailed sampling of respiration before and after irrigation in the ancillary experiment (see below).

Tillage was followed by immediate and significant increases in CO_2 efflux in the rototilled and disked soils (Fig. 3c, Table 2). The effect was more pronounced in the disked soil, which was three times higher than the control at 0.25 h after tillage. The CO_2 efflux of all soils peaked at 6 h after tillage, when the soil temperatures at the 7.5-cm depth were the highest of the experiment (34.6 to 35.8°C). The increases in CO_2 efflux in the rototilled and disked soils were short-lived, lasting for less than 12 h after the soil disturbance. The CO_2 efflux of all treatments increased after irrigation. The control soil had the highest response, with a more than 10-fold increase that took 42 h to decline back to pre-irrigation levels. The CO_2 efflux of the rototilled soil had a fivefold rise, while the disked soil increased 2.5 times relative to pre-irrigation levels.

Ancillary Experiment

Initially, the soils in this experiment had an average moisture content of 124 g H_2O kg^{-1} dry soil in the top 0 to 15 cm, which falls within the range of the soil moistures of the main experiment before irrigation (Fig. 1 and 4). Within 0.8 h after irrigation, the soils from the three treatments reached relatively uniform moistures, ranging from 139 to 148 g H_2O kg^{-1} dry soil, that is, −11.5 to −18.5 kPa (Fig. 4). Unlike the disked and the control soils, the moisture of the rototilled soil remained high after irrigation and throughout the duration of the ancillary experiment.

Frequent sampling in this experiment revealed a significant increase in respiration in the control and disked soils after irrigation (Fig. 4). As in the main experiment, the effect was of greatest magnitude in the control soil, which increased more than sixfold within 0.8 h of irrigation. The rototilled soil had a higher respiration rate before irrigation than the other two treatments, and it did not change after irrigation.

Irrigation increased the CO_2 efflux of the control and rototilled soils (Fig. 4). A significant increase in CO_2 efflux of the control and rototilled soils occurred between 1.3 h before irrigation and 0.8 h after irrigation. The effect was ephemeral in both treatments, but the increase was more pronounced and longer-lived in the control soil. For the control soil, the responses in CO_2 efflux of the main experiment were larger than those of the ancillary experiment (Fig. 3c, 4c). Irrigation had only a slightly positive but nonsignificant effect on the CO_2 efflux of the disked soil.

DISCUSSION

Our results show that tillage caused bursts of CO_2 efflux that may be best explained by the physical release of CO_2 from the soil, because the soil respiration rate did not increase simultaneously. Previous studies have shown that tillage and simulated tillage did not increase respiration rate, and even caused a short-lived decline in respiration that was attributed to microbial stress and changes in microbial community structure (Calderón et al., 2000, 2001). The ventilation of the soil after tillage is thought to cause a sudden decrease in the partial pressure of CO_2 in the soil air, which is followed by a sudden release of CO_2 from the soil solution, and subsequent efflux of CO_2 from the soil surface (Reicosky and Lindstrom, 1993; Reicosky et al., 1995, 1997; Rochette and Angers, 1999; Ellert and Janzen, 1999). In this experiment, the disked soil had the highest CO_2 efflux values following tillage, supporting the idea that the amount of exposed soil surface and the size of the surface voids increase CO_2 efflux after tillage (Reicosky and Lindstrom, 1993). In contrast, irrigation was followed by an increase in CO_2 efflux that appears to be associated with both physical processes and increased biological activity. Tillage also increased net mineralization and nitrification, suggesting that the physical disruption of soil increases the availability of organic nitrogen, and/or microbial community structure changes in a way that enhances these processes for a considerable period of time after the tillage event.

In the Yolo silt loam, the higher ammonium, nitrate, and DON concentrations after tillage indicate increased mineralization after rototillage and disking compared with the control. Moisture availability during the first 7 d of the post-tillage period before irrigation was high enough to support C and N mineralization rates of approximately 50 to 75% of maximum rates, based on data collected on a soil of similar clay content and greater range of soil water-filled pore space (WFPS) (Franzluebbers, 1999). During this 7-d period, the WFPS was approximately 19 to 23% for the rototilled soil, 17 to 24% for the disked soil, and 28 to 50% for the control soil. Although DON was greater in tilled than control treatments, it declined in all treatments during this initial post-tillage period, but it increased after irrigation. This suggests a close relationship between moisture and DON. A low R^2 value of 0.41 for the linear regression between DON and gravimetric moisture, however, suggests that a combination of factors are responsible for the fluctuations in DON (data not shown). Other studies have shown increases in ammonium and nitrate after tillage (Silgram and Shepherd, 1999). We hypothesize that the source of this mineral N is previously protected, N-rich organic matter that is made available to microorganisms when the soil is disrupted. The demand for organic and mineral N by the soil microbiota was not sufficient to prevent the higher levels of ammonium, nitrate, and DON in the disturbed soils from accumulating. The microbial biomass might have been an ephemeral sink for readily available organic or mineral nitrogen, as suggested by the short-lived response in MBN after tillage. It is possible that microbial N uptake in the disturbed soils was limited by C availability or microbial stress (Calderón et al., 2000), which could also explain the lack of change in MBC.

Disking did not affect the MBN of the 0- to 3-cm layer as dramatically as rototillage, suggesting that the soil disturbance, mixing pattern, and aggregate disintegration in the disked soil is less detrimental to the MBN of the uppermost layer of soil. The 0- to 3-cm layer of the rototilled soil may provide a particularly unfavorable environment for the microbial biomass. It may be more vulnerable to fast desiccation because of the reduced density and destruction of macroaggregates. This may be related to a mulch effect, in which the surface layer of the rototilled soil forms a dry layer that is not connected to lower layers through capillary water, and prevents moisture loss from deeper layers of soil.

Irrigation, like tillage, had no discernible effect on the MBC, suggesting that the total microbial biomass is resilient to disturbance, at least at the relatively high moisture availability of this study. Air-dry soils, however, show large increases in MBC and respiration when rewet because microbial immobilization rapidly occurs in response to the increased availability of carbon substrates after severe drought (Zaady, 1996; Lundquist et al., 1999). Sampling frequency clearly plays a role in describing differential responses of tillage treatments to a change in moisture. In addition, the tillage treatments had different rates of drying after tillage. Therefore, the different treatments were not brought to exactly the same moisture content after irrigation. For this reason, precise differences between treatments in responses to irrigation are difficult to assess. In the same manner, comparisons between the main experiment and the ancillary experiment have to be done cautiously. For example, the CO_2 efflux of the control soil during the main experiment was higher than that of the control soil during the ancillary experiment. This difference may be due to slightly lower moisture in the ancillary experiment, or to differences in the timing and mode of irrigation between the two experiments. Both experiments showed, however, that CO_2 efflux was greater after irrigation when tillage had not previously occurred. In contrast, net N mineralization after irrigation was higher in previously tilled soils. Further work is needed to explain these apparent differences in microbial C and N dynamics in response to tillage.

Long-term effects of tillage may not merely be the additive effects of single tillage events. The initial flush of CO_2 after a tillage event accounts for a very small proportion of total soil C (Roberts and Chan, 1990; Kessavalou et al., 1998). Tillage, however, increases the porosity of the upper layer of soil and consequently lowers the thermal conductivity. This may result in a soil temperature regime with daily maxima of several degrees higher than nontilled soils (Hillel, 1980). Higher temperatures may result in higher microbial activity in the upper layers of soil, resulting in increased C mineralization rates in tilled soils that may last well into the growing season and account for substantial CO_2 losses (e.g., 0.5 vs. 0.2% of total soil C in moldboard plowed

vs. no-till soils during a 60-d period) (Dao, 1998). More information on soil microbial processes in the short and long term after tillage is required to mechanistically explain rates of soil carbon sequestration under different tillage regimes (Kern and Johnson, 1993; Lee et al., 1993; Ellert and Bettany, 1995).

In summary, use of different tillage implements causes different rates of physical release of CO_2 from the soil surface, and elicits changes in N dynamics that linger for at least two weeks after tillage. Responses to subsequent irrigation appear to depend on the amount of previous CO_2 efflux after tillage, and microbial responses to the type of tillage disturbance, which may in turn affect soil microbial activity and respiration. Thus, different tillage implements have different effects on soil and atmospheric environmental quality due to their effects on C and N dynamics and subsequent losses.

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