Enhancing Inorganic Carbon Sequestration by Irrigation Management in California

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Summary

We conducted a field study to determine if the distribution and amount of soil inorganic carbon was changed by the application of treated effluent for irrigation compared to fresh-water irrigated soils. The main site for the study was in a wastewater utilization area near Bakersfield, Calif., that had received varying amounts of treated effluent for 70 years. At the time, the sampled cotton was growing at the site. A nearby field, irrigated with fresh water, also was sampled for comparison. Significant depletions of carbonate were found in the upper 2m of all irrigated fields, compared to non-irrigated fields. Carbonate did not accumulate in soils with textures as coarse as loamy sand. Differences in carbonate content among fields irrigated with treated effluent and fresh water were a function of both soil texture and water quality. Soils with carbonate contained both natural pedogenic carbonate and carbonate inherited from the parent material. It was not possible to isolate and measure the young pedogenic carbonate that might have resulted from effluent utilization. Total carbonate content and clay-size carbonate was more abundant at sites irrigated with treated effluent than at sites irrigated with fresh water, indicating that effluent had increased carbonate precipitation. Stable isotope analyses of carbon and oxygen indicated that a significant amount of the carbonate found below 2.5 meters depth in the treated-effluent irrigated field was pedogenic. The pedogenic carbonate was a mixture of young and old carbon according to ^{14}C dating of the carbonate. More of the carbonate was "young" carbonate at shallow depths of the soil compared to deeper in the soil profile. This is additional evidence that treated-effluent irrigation contributes to carbonate precipitation. Treated-effluent irrigation can increase soil inorganic carbon sequestration in arid and semiarid region soils and it should be used as another method for balancing the increase in CO_2 in the atmosphere from anthropogenic activity.

Objectives

Our objectives are to 1) Examine the extent of carbonate precipitation in treated-effluent irrigated fields through reconnaissance surveys; 2) Identify the factors that control soil carbonate dissolution/precipitation under treated-effluent irrigation; 3) Determine the treated-effluent irrigation management that maximizes inorganic carbon sequestering in arid region soils; and 4) Test the conceptual model presented in the proposal.

Approach and Procedures

To address objective 1, we contacted wastewater treatment plant operators between Bakersfield and Lodi, Calif., to determine if they had accessible fields irrigated with treated effluent. We located wastewater treatment plants in Bakersfield, Fresno, Manteca, and Lodi that appeared to be suitable sites based on soil survey reports and discussions with the plant managers. At each of

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these sites, we attempted to collect samples using a hand auger to a depth of 6 meters. In some sites, a perched water table restricted our sampling depth. At another location, hardpan restricted the sample depth. In addition to sample collection from wastewater-irrigated fields, in some locations we were able to sample fields that had the same soils, according to published soil survey reports, that had been irrigated with fresh water. We unsuccessfully attempted to use a department Geoprobe to collect samples from a field with a high water table.

We addressed objectives 2 and 4 using standard laboratory methods for pH, EC, total carbonate, and total organic C. We measured the particle size distribution of untreated and carbonate-free samples using a Beckman-Coulter LS230 Laser particle size analyzer. We examined selected samples using an electron microprobe. We also carried out isotopic analysis, including $\delta^{13}C$ and $\delta^{18}O$. Selected samples were sent to Beta Analytic INC for radiocarbon age dating.

Unfortunately, we were not able to fully meet objective 3, due to the complexity we encountered while addressing the other objectives.

Results

The four sites selected provided a precipitation gradient from Bakersfield, with 125 mm mean annual precipitation, to Lodi, with 400 mm. We expected that the depth to carbonate would reflect the precipitation gradient. Our preliminary survey indicated a large carbonate concentration in soil irrigated for 70 years with treated effluent in the Bakersfield area, and no carbonate in a field irrigated with fresh water within one kilometer of the treated-effluent irrigated field. Subsequent investigations indicated large spatial variability of carbonate presence or absence and that the two fields had sufficiently different textures to influence the carbonate distribution.

Table 1. *Mean carbonate content in the studied sites at Bakersfield.*

Type of irrigation water	Carbonate content †			
	0-2 m		2-4m	
	# of profiles	Mg/ha/depth	# of profiles	Mg/ha/depth
Treated-effluent	7	92.6 b	4	1172.0 a
Fresh-water	6	68.2 b	3	8.7 b
No cultivation	2	323.6 a	1	192.2 ab

† Within a column, values followed by the same letter do not differ significantly (0.05 probability level).

Each of the sites sampled along the transect had carbonate accumulations (*figs. 1&2*), but the depth to the accumulations was not clearly a function of the mean annual precipitation. For example, the Lodi carbonate was found above a cemented pan at depths of <1m (*fig. 2b*), while the Bakersfield carbonate was found at depths exceeding 2m (*fig. 1*) and the Fresno (about 10 years of treated-effluent irrigation) carbonate was found at depths exceeding 4m (*fig. 2a*). We returned to Bakersfield to further examine the relationship between soil properties and carbonate distribution. The total carbonate content suggests that the irrigation water quality does affect the amount of inorganic carbon content in the soil profile (*table 1 and fig. 1*). In order to assess the size of the affect, it was necessary to isolate the modern carbonate from the old carbonate. We could not do this unequivocally.

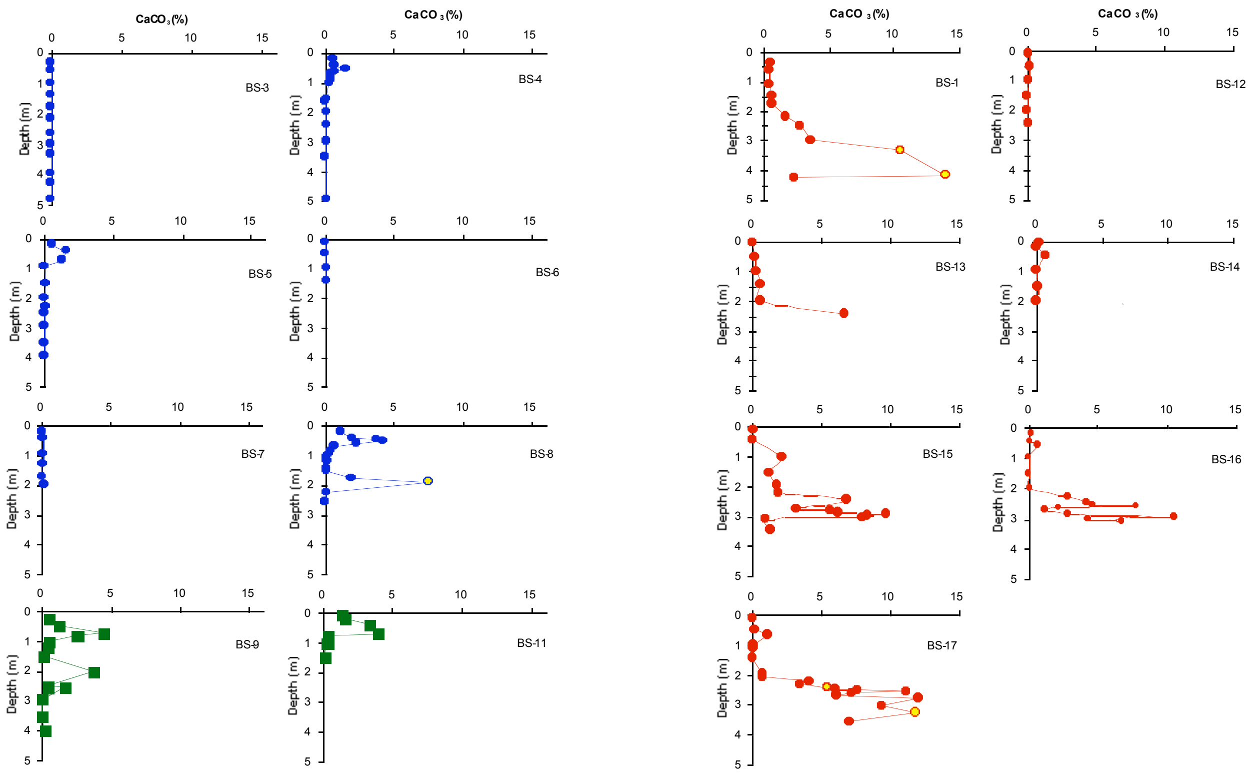

Figure 1. Carbonate distribution in three different sites. Fresh water (blue); no irrigation (green) and treated-effluent irrigated (red). Sample points in yellow were dated by ^{14}C analysis.

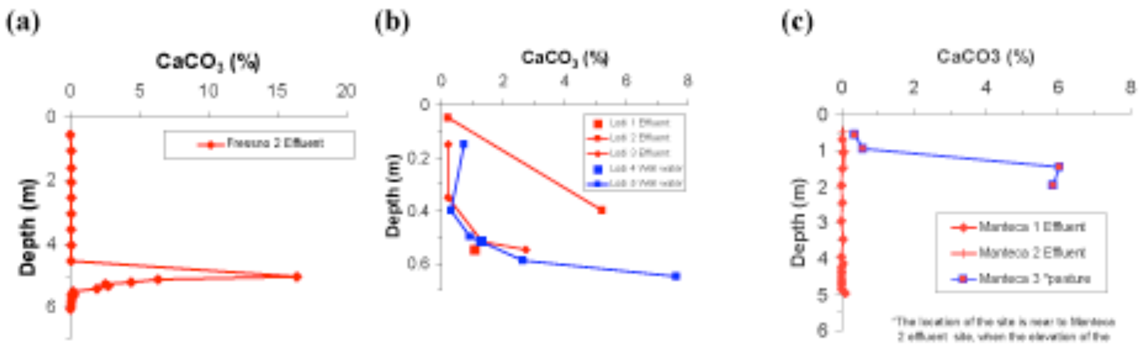

Figure 2: Carbonate distribution in fields irrigated with fresh water (in blue) and treated effluent (Red); (a) In Fresno, Calif., for about 10 years; (b) Lodi, Calif., for about 40 years, and (c) Manteca, Calif., for about 20 years.

Additional supporting evidence for the effect of water quality on the inorganic carbon content in the soil profile came from the calcite particle size distribution in the soil profile. We analyzed the particle size distribution before and after carbonate removal (HCl 5%) using a laser particle size analyzer – Coulter LS 230 (Eshel et al. 2004). An increase in clay due to carbonate removal suggests that the carbonate acted as a cementing agent, and depletion in clay due to carbonate removal suggests the presence of clay size carbonate.

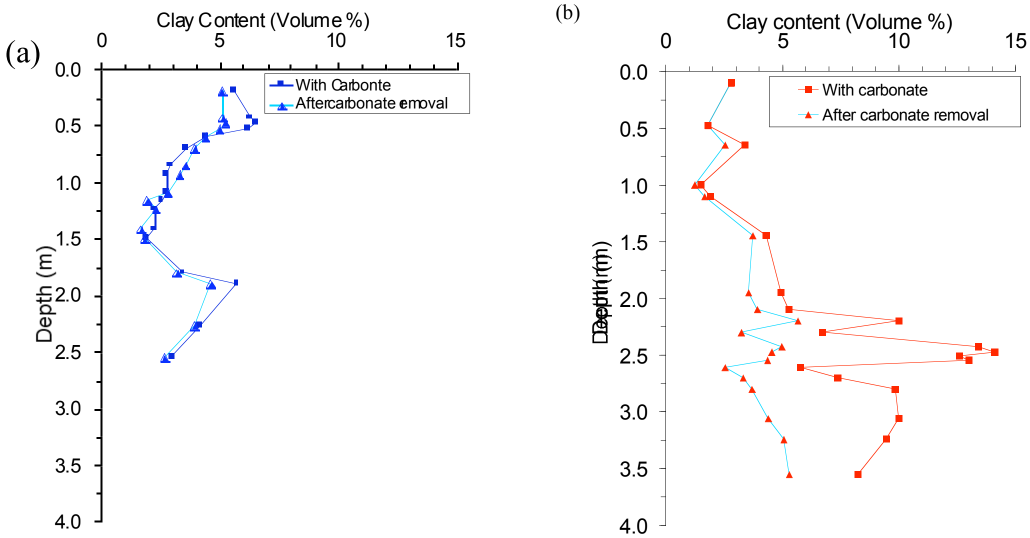

Figure 3. The clay content before and after carbonate removal. (a): fresh-water irrigation (BS-8), (b): treated-effluent irrigation (BS-17).

In fresh-water irrigation, no significant addition or depletion in the clay content was noted along the profile following carbonate removal (*fig 3a*).

In the treated-effluent irrigated field, depletion in the clay content was noted after carbonate removal, mainly in the deeper half of the studied profile, which suggests that a significant fraction of the carbonates were present in the clay size fraction (*fig 3b*). McCaslin and Lee-Rodriquez (1979) reported a similar pattern.

It is important to mention that during soil sampling in the treated-effluent irrigated field we found the layer rich in carbonate to be very hard and repeatedly found a saturated layer on the top of it, even a couple of months after the last irrigation event. In thin sections of these rich carbonate layers, we found a mixture of calcite, clay, and quartz. These morphological findings suggest that this carbonate was cemented in situ. On the other hand, the carbonates in one of the profiles at the fresh-water irrigated field below 2 m, were in a well-aggregated finger-shaped calcite concentration. The calcite-rich concentration also was a mixture of clay, quartz, and calcite. Unfortunately, due to our difficulties in sampling undisturbed soil profiles with the Geoprobe, we could not point to the exact orientation of thin sections and take the observation further.

The amount of carbonate found in the fields irrigated with treated effluent (*table 1*) far exceeded the amount that could have precipitated due to effluent irrigation alone, which suggests that we found a mixture of old pedogenic carbonate or deterial and new carbonate due to effluent irrigation. In order to clarify this assumption, we conducted an isotopic analysis of the soil carbonate.

Several soil samples from Bakersfield and one from Fresno were sent to Beta Analytic Inc. for radiocarbon dating for the soil inorganic carbon (SIC) fraction. The sample from Fresno (Fresno 2, depth of 5-5.1 m) had a date of >37,170 years, so we did not focus on this site. For samples from Bakersfield, the results were found to be equivocal. The radiocarbon analyses suggest ages of 1,400 to 7,030±120 years for this site (*table 2*). These ages suggest that the bulk

SIC in the fresh-water irrigated filed in Bakersfield is younger then the SIC in the treated-effluent irrigated field. Also, a trend was noted in the radiocarbon dating in the samples from the treated-effluent irrigated field: the deeper the sample, the older the carbonate (*table 2*).

Table 2. *Radiocarbon dating values of selected samples from Bakersfield.*

Sample #	Depth (m)	Radiocarbon age (Years BP)
----------------------- Fresh-water irrigation -----------------------		
BS-8/15	1.9	1410±40
------------------------- Treated-effluent irrigation --------------------------		
BS-17/11	2.4	4100±40
BS-17/19	3.24	6080±40
BS-1/9-10	3-4	7030±120

Several earlier studies suggest that stable isotope ratios of carbon and oxygen can be a useful tool for identification of pedogenic carbonate in soils and to determine their proportion of the total carbonate (Magaritz and Amiel, 1980; Magaritz and Amiel, 1981; Rabenhorst et al., 1984; Amundson and Lund 1987; Mermut et al. 2000). Having that in mind, we carried out a stable isotope analysis of C and O of the SIC for selected samples from profiles BS-4, BS-8, BS-9, BS-15, and BS-17. The analysis was made by isotope ratio mass spectrometers at the Stanley V. Margolis Stable Isotope Laboratory (SIL) at the Department of Geology at the University of California, Davis. In addition to several samples, we had the δ^{13}C and the total C of the soil organic carbon (SOC) analyzed by the UC Davis Stable Isotope facility.

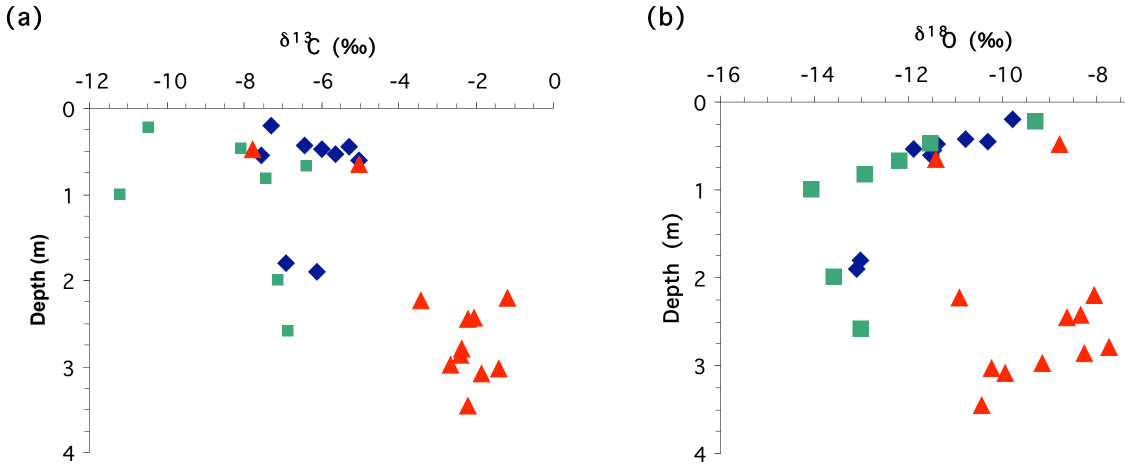

Figure 4. The SIC δ^{13}C (a) and δ^{18}O (b) distribution of selected samples from profiles BS-4, BS-8, BS-9, BS-15 and BS-17 with depth distribution in three different sites. Fresh water (blue dots); no irrigation (green squares); treated-effluent irrigated (red triangles).

We found similar δ^{13}C values (-5‰ to -8‰) for the SIC in the fresh-water and treated-effluent irrigated fields at the 0-2 m depths. At the no-irrigation site, the δ^{13}C values were more negative (-6‰ to-11‰). On the other hand, at the 2-4 m depth, the δ^{13}C values for the treated-effluent irrigated field were less negative (-1‰ to -3‰), relative to the fresh-water irrigation field and the no-irrigation site (-6‰ to -7‰) (*fig 4a*).

The δ^{18}O values were more negative with depth for the 0-2 m depth at the three sites (*fig 4b*). This trend also was noted in the treated-effluent irrigated field at the 2-4 m depth.

In order to complete the picture, selected samples from the profile BS-4, BS-8, BS-9, BS-15 and BS-17 also were analyzed for the SOC content and its isotopic signature. The SIC were removed from the sample by acid fumigation (Harris et al. 2001). In both irrigation management systems, SOC was depleted along the profile up to depth of 3 m. the majority of the SOC lost occurred in the plow horizon (*fig 5a*). No significant difference was noted in the SOC content between the irrigation management systems, even though it appears that the fresh-water irrigation field had lost slightly less in the upper 2 m of the profile and this trend was reversed in the lower 2 m of the profile. The SOC δ^{13}C profiles of the fresh-water irrigation and no-irrigation sites had a similar trend of depletion in ^{13}C in the upper meter of the profile (δ^{13}C values change from -25‰ at the top to -21‰ at 1-m depth with no-irrigation; δ^{13}C values change -24‰ to -20.5‰ in fresh-water irrigation). This trend changes direction as ^{13}C increases in the next 3 m where it achieved the values of the top soils (*fig 5b*). The SOC of the treated-effluent irrigation is less rich in ^{13}C in the top soil and stays the same in the first m of the profile (δ^{13}C =22$\pm$0.5‰). Similar values were noted for an orchard irrigated with treated effluent for about 40 years in Israel (Affek et al. 1998). Deeper in the profile (2-4 m), the SOC is much less rich in ^{13}C (δ^{13}C values of -21.5‰ to -18‰), which may be a result of the organic carbon derived from the effluent (δ^{13}C= -23‰ Affek et al. 1998) and microbial activity at this depth (personal communication with Dr. Horwath).

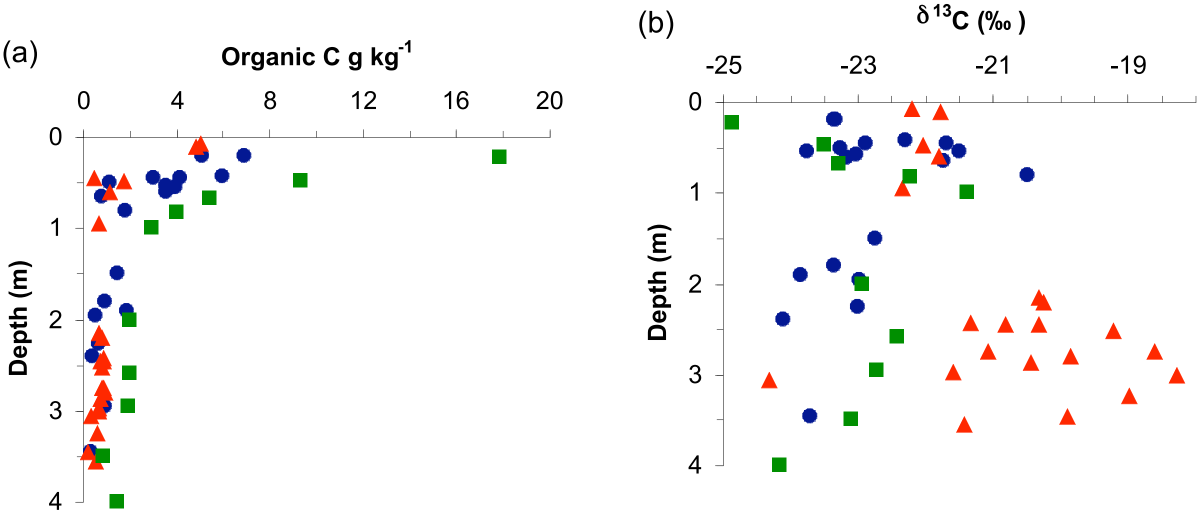

Figure 5. (a) the total organic C and (b) its δ^{13}C signature of selected samples from profiles BS-4, BS-8, BS-15 and BS-17 with depth. Fresh water (blue dots); no irrigation (green squares); treated-effluent irrigated (red triangles).

Discussion

It is well known that carbonate accumulation in arid soils is a common process. The accumulation can be a result of all or part of the following three major processes: redistribution of detrital carbonate in the profile or redistribution of exogenous material (e.g., dust) and in situ formation due to mineral weathering. The redistribution can result from, as commonly suggested, dissolution and precipitation of the carbonate mineral or by transportation as colloidal suspensions (Baghernejad and Dalryple 1993; Neaman et al. 2000).

As for carbon sequestration, disagreement exists in the literature as to whether dissolution of solid carbonate should be considered as sequestration (e.g., Suarez, 2000; Nordt et al. 2000; Drees et al., 2001) or whether precipitation of carbonate solid should be considered as sequestration (e.g., Lal and Kimble 2000; Eswaran, et al. 2000; Scharpenseel et al. 2000; Ryskov et al. 2000). In this study, we consider a transfer of carbon from the gas phase to the liquid and/or the solid phase as sequestration.

Given the high loading rates of treated-effluent, it is not surprising that the mean annual precipitation is not closely related to the depth of carbonate precipitation. It is somewhat surprising that carbonate distribution is strongly related to the original particle size distribution. The landscape and soil in Bakersfield appear to be young, probably <10,000 years BP based on the lack of soil horizons.

At Bakersfield we found a large variability in carbonate content in both fields. Our original finding that no carbonate had accumulated in the fresh-water irrigated site appears to be a function of the slightly coarser (sandier) texture of the soil at the profile location. Multiple sample locations in the Bakersfield disposal area indicate that coarse textured sites did not accumulate carbonate within the sample depths. Thus, if fields are to be managed to accumulate inorganic carbon, those with textures finer than loamy sand need to be selected. A significant depletion of carbonate was noted in the root zone (0-2 m) of the two irrigated fields. No significant difference in carbon depletion was noted between the treated-effluent and fresh-water irrigated fields (*table 1*).

The old age of the carbonates from the sample from the treated-effluent irrigated field at Fresno indicates that a buried, older soil underlies the young modern soil. This finding is in agreement with the morphological evidence (more reddish color soil at depth of 3 m) in the studied profile, which suggested a buried b_k horizon.

The relatively young age of the carbonate from the field irrigated with treated-effluent at Bakersfield indicates a possible dilution of the older material with young carbonate. The finer size of the carbonate, as indicated by solubility and the comparison of particle size distribution in carbonate free and carbonate present samples supports the idea that a younger carbonate is mixed with older carbonate. The isotopic analysis suggests two possible scenarios for the Bakersfield case**:**

***Senario1:** The effluent contributes to the carbonate isotopic signature at the layer of accumulation found between 2 and 4 m in the treated-effluent irrigated field.*

In order to test the probability of this scenario we plotted our results combined with the general model proposed by Cerling, (1984) (*fig. 6*). The model suggested a relationship between $\delta^{18}O$ and $\delta^{13}C$ in native modern carbonate and climate. The model considers the variation in vegetation biomass, gas exchange with the atmosphere and the rain isotopic composition. Also it assumes that all carbonate in the soils are pedogenic and no deterial carbonate remains. It can be clearly observed that the no-irrigation, and the fresh-water irrigation carbonate samples fit well within the range of "normal" carbonate in the model. On the other hand, the majority of the carbonate analyses from the treated-effluent irrigation field are above the 30% threshold for atmospheric CO_2 contribution to the soil atmosphere, which is the range of expected values for "normal" soil carbonates (Cerling 1984). We explain this finding by suggesting that the different $\delta^{13}C$ signature of the SOM of the treated-effluent irrigated field may be affected by the organic carbon in the effluent (*fig. 5b*) and the large volume of water or that the carbonate has a strong "atmospheric carbon" signal indicating that it precipitated as part of the pedogenic process.

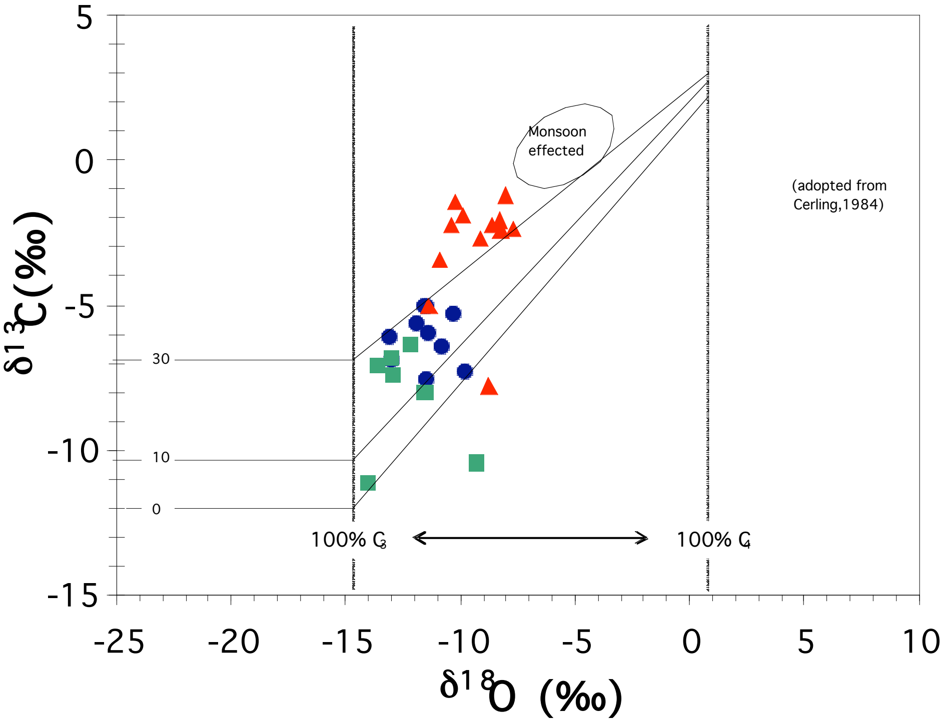

Figure 6. The relationship between $\delta^{18}O$ and $\delta^{13}C$ of SIC from Bakersfield, Fresh water (blue dots); no irrigation (green squares); treated-effluent irrigated (red triangles). The solid lines represent a "normal" carbonate precipitate in arid and sub-humid climate conditions as suggested by Cerling (1984), for the range of vegetation (dashed lines), precipitation and gas exchange (atmospheric contribution).

Scenario 2: *The carbonate found in the treated-effluent irrigated field in Bakersfield is a mixture of old and recent carbonate, with a considerable anthropogenic contribution.*

In order to estimate the fraction of pedogenic carbonate from the total carbonate, we used Equation 1, adopted from Magaritz and Amiel (1980). In our calculation, we assumed $\delta^{13}C_{Parent} = -1.0 \pm 1‰$, which is a common value for parent material calcite, and for $\delta^{13}C_{soil} = -11.2‰$, which is the lowest value in the no irrigation site. The last is in close agreement with the value of -11.0 found in a site near ours by Amundson and Lund (1987).

$$\text{pedogenic}(\%) = \left(\frac{\text{ä}^{13}\text{C}_{\text{measured}} \quad - \quad \text{ä}^{13}\text{C}_{\text{Parent}}}{\text{ä}^{13}\text{C}_{\text{soil}} \quad - \quad \text{ä}^{13}\text{C}_{\text{Parent}}} \right) \times 100 \qquad [1]$$

With the knowledge of the relatively high δ^{13}C values for the treated-effluent irrigated samples, it was not surprising to find that the percentage of pedogenic carbonate in the majority of these samples was low, compared to the no-irrigation and fresh-water irrigation samples (*fig. 7a*). However, when we multiplied the percentage of pedogenic carbonate with the total amount of carbonate, the picture looks totally different (*fig. 7b*). The results suggest that a large amount of pedogenic carbonate accumulates in the treated-effluent irrigated soils between 2.5-3.5 m, in common with the shape of the accumulation profile. At the fresh-water irrigation site, the accumulation was similar to the no-irrigation site in the upper meter and also in the 2-m depth.

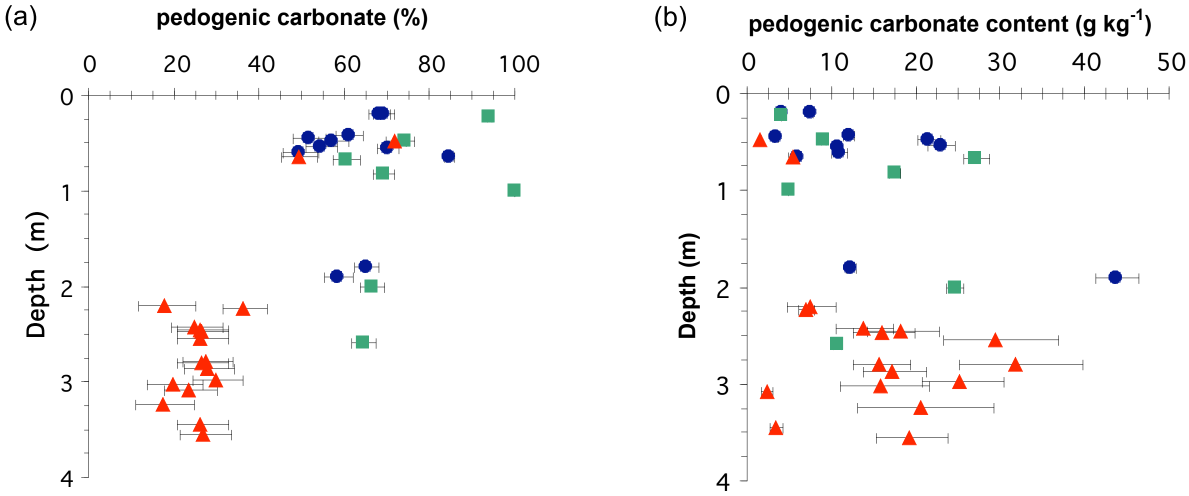

Figure 7. The estimated pedogenic carbonate calculated by Eq.1 as a function of depth (a) expressed as a percentage of the total carbonate and (b) as total mass. Fresh water (blue dots); no irrigation (green squares); treated-effluent irrigated (red triangles). The error bars represent the range of calculated values applying ±1 in the $^{13}\text{C}_{\text{Parent}}$.

Both scenarios suggested that a large accumulation of carbonate has occurred in the treated-effluent irrigated field at Bakersfield.

If we assume that the sources of acidity needed for deterial and/or eolian $CaCO_3$ dissolution have come mainly from carbonic acid, the depletion of carbonate in the root zone at the irrigated fields can be considered as more inorganic C sequestration. From the observations in the field and from the isotopic analysis we found that the precipitation of carbonates at the treated-effluent irrigation below 2 m probably occurred in moist environment. Under this condition, it is reasonable to assume a closed system related to CO_2. Under these conditions, it may be considered as carbon sequestration as well.

We assume that the effluent quality has changed significantly over the 70-year history of Bakersfield, and we do not know how the changes have affected carbonate precipitation. We assume that the treated effluent is higher quality now than in the past, and this may also be partly responsible for the carbonate distribution in the soil profile. Under both irrigation management systems, SOC depletion along the studied depth (4 m) was noted (*fig. 5a*). In the soils irrigated with fresh water and the no-irrigation soils, the depletion in the ^{13}C content found in the first meter of the profile is commonly found in soil. This depletion is related to the fact that easily metabolized components of the organic matter (e.g., organic acids) are richer in carbon 13. The fact that the δ^{13}C values become more negative in the next 3 m suggests that some of the enrichment in carbon 13 is from SOM fractions that are usually easily decomposed by microorganism. Here, they have been leached deep into the profile. This finding supports the results from a recent lysimeter study (Fine et al. 2002). The δ^{13}C signature of SOC in treated-effluent irrigation soils from 2-4 m was found to be more positive than carbon from the first meter (*fig. 5b*), which may indicate that microbial activity is occurring in that deep layer.

The depth of carbonate in the treated-effluent irrigated sites appears to be well below the zone of most active root growth. This may indicate that additional processes have an important role in carbonate precipitation in treated-effluent irrigated fields. Microorganisms are considered to have an important function in carbonate precipitation in arid soils (Phillips et al. 1987; Monger et al. 1991; Monger and Galleos 1999). Fine et al. (2002) found that the TOC concentrations in the leachate from lysimeters irrigated with effluent can be up to seven times higher than equivalent treatments irrigated with fresh water. The high concentrations of organic carbon (TOC = 40-250 mg/l in effluent irrigation and TOC = 5-55 mg/l in fresh-water) below the root zone may enhance microbial activity below the root zone in cases of treated-effluent irrigation and may play an important role in carbonate precipitation.

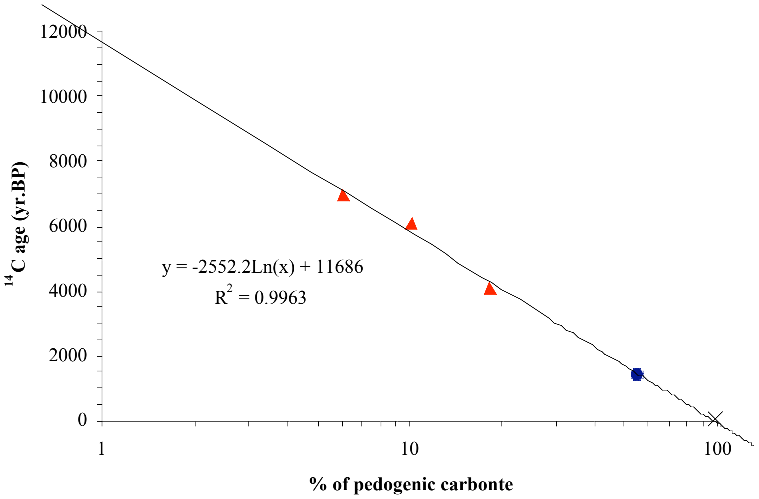

Figure 8. The radio carbon age as function of the percentage of carbonate, the values for radio carbon ages taken from Table 2. Fresh water (blue dot), treated-effluent irrigated (red triangles) and estimated value of 90 years with 100 present pedogenic (black X).

When we plotted the radiocarbon age as a function of estimated pedogenic carbonate concentration, we found that the y intercept is in good agreement with the estimated age of the soil (*fig. 8*). If we consider that the detrital carbonate was completely reset to modern at the time of fan deposition (Pendall et al. 1994), the 11 ka age of detrital carbonate supports our argument that the treated-effluent irrigation increased carbonate precipitation. Since the soil we studied (Kimberlina series) is believed to be formed from recent alluvium on young alluvial fans originating from local granitic and sedimentary rocks (Soil Survey Staff 1988), the presence of a mixture of detrital pedogenic carbonate is very reasonable. As far as we know, this is the first time that this kind of relationship has been demonstrated.

Conclusions

The isotopic analysis of the SIC from Bakersfield is in good agreement with both scenarios: the 2-4 m depth in the treated-effluent irrigated field is a mixture of deterial and newly formed carbonates and/or that the layer of SIC accumulation was affected by the treated-effluent irrigation. We could not specify which better represents the "story" behind the field, which leads us to believe that it is a combination of both of them.

Even though we found a large variability of carbonate content in both fields, a significant depletion of carbonate was noted in the root zone (0-2 m) of the two irrigated fields. No significant differences in carbon depletion were noted between the treated effluent and fresh-water irrigated fields. Given that the sources of acidity needed for $CaCO_3$ dissolution came mainly from carbonic acid, this depletion can be considered as inorganic C sequestration. Below the root zone (2-4 m), more total and pedogenic carbonate was found in the field irrigated with treated effluent, which also may be considered a form of carbon sequestration.

This study provides some of the first evidence of a possibility of how water quality effects C sequestration as SIC. It is clear that soils of medium texture should be selected for effluent disposal or utilization if carbon sequestration is also part of the management goals. Frequent effluent additions will lead to dissolution, leaching and precipitation of carbonate if the effluent management is coordinated with knowledge of soil water holding capacity and plant water use. Effluent quality probably plays a role in where the carbonate will precipitate and how much will precipitate, but we do not have data on the treated-effluent quality over the 70 years of use in Bakersfield to determine what the role or roles might be. The study well demonstrates the complexity of this system and the need for more study.

References

Affek H.P., D. Ronen, and D. Yakir. 1988. Production of CO2 in the capillary fringe of a deep phreatic aquifer. *Water Resources Research* 34:989-996.

Amundson R.G., and L.J. Lund. 1987. The stable isotope chemistry of a native and irrigated typic natargid in the San Joaquin Valley of California. *Soil Science Society of America Journal* 51:761-767.

Baghernejad M. and J.B. Dalymple. 1993. Collodial suspentions of calcium carbonate in soils and their likely significance in the formation of calcic horizon. *Geoderma.* 58:17-41.

Cerling T.E. 1984. The stable isotopic composition of modern soil carbonate and its relationship to climate. *Earth and Planetary Science Letters.* 71:229-240.

Eshel, G., G.J. Levy, U. Mingelgrin, and M.J. Singer. 2004. Critical evaluation of the use of laser diffraction for particle size distribution analysis**.** *Soil Science Society of America Journal.* 68:736-743.

Eswaran H., P.F. Reich, J.M. Kimble, F.H. Beinroth, E. Padmanabhan, and P. Mocharoen. 2000. Global carbon stocks. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 15-26. CRC/Lewis Publ., Baca Raton, FL.

Fine, P., A. Hass, R. Prost, and N. Atzmon. 2002. Organic carbon leaching from effluent irrigated lysimeters as affected by residence time. *Soil Science Society of America Journal* 66:1531-1539.

Harris, D., W.R. Horwåth, and C. Van Kessel . 2001. Acid fumigation of soils to remove carbonate prior to total organic or carbon -13 isotopic analysis. *Soil Science Society of America Journal* 65:1853-1856.

Lal R., and J.M. Kimble. 2000a. Pedogenic carbonate and global carbon cycle. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 1-14. Boca Raton:CRC/Lewis Publ.

Lal R., and J.M. Kimble. 2000b. Inorganic carbon and global C cycle: research and development priorities. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 291-302. Boca Raton: CRC/Lewis Publ.

Magaritz M., and A.J. Amiel. 1980. Calcium carbonate in a calcareous soil from the Jordan Valley, Israel: It origin revealed by stable carbon isotope method. *Soil Science Society of America Journal* 44:1059-1062.

Magaritz M., and A.J. Amiel. 1981. Influence of intensive cultivation and irrigation on soil properties in Jordan Valley, Israel: Recrystalization of carbonate minerals. *Soil Science Society of America Journal* 45:1201-1205.

Mermut A.R., Amundson R., and Cerling T.E. 2000. The use of stable isotopes in studying carbonate dynamics in soils. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 65-85. Boca Raton:CRC/Lewis Publ.

Monger H.C., L.D. Daugherty, W.C. Lindemann, and C.M. Liddell. 1991. Microbial precipitation of pedogenic calcite. *Geology* 19:997-1000.

Monger H.C., and R.A. Galleos. 1999. Biotic and abiotic processes and rates of pedogenic carbonate accumulation in the Southwestern United States – Relationship to atmospheric CO2 sequestration. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 273-287. Boca Raton:CRC/Lewis.

Neaman, A., A. Singer, and K. Stahar. 2000. Dispersion and migration of fine particles in two palygorskite-containing soils of Jordan Valley. *Journal of Plant Nutrition and Soil Science* 163:537-547.

Nordt L.C., L.P. Wilding, and L.R. Drees. 2000. Pedogenic carbonate transformation in leaching soil system: implication for the global C cycle. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 43-46. Boca Raton:CRC/Lewis.

Pendall E.G., J.W. Harden, S.E. Trumbore, and O.A. Chadwick. 1994. Isotopic approach to soil carbonate dynamics and implications for paleoclimatic interpretations. *Quaternary Research* 42:60-71

Phillips S.E., A.R. Milnes, and R.C. Foster. 1987. Calcified filaments: an example of biological influences of calcrete in South Australia. *Australian Journal of Soil Research*. 25:405-528.

Rabenhorst M.C., L.P. Wilding, and L.T. West. 1984. Idenification of pedogenic carbonate using stable carbon isotope and microfabric analysis. *Soil Science Society of America Journal* 48:125-132.

Ryskov, Y.A., A.V. Borisov, S.A. Oleinik, E.A. Ryskova, and V.A. Demkin. 2000. The relationship between lithogenic and pedogenic carbonate fluxes in steppe soils, and Regularities of their profile dynamics for the last four millennia. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 121-134. Boca Raton:CRC/Lewis.

Scharpenseel H.W., A. Mtimet, and J. Freytag. 2000. Soil inorganic carbon and global change. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 27-42. Boca Raton:CRC/Lewis.

Soil Survey Staff, 1988. Soil survey, Kern County, California, Northwestern part. USDA, Soil Conservation Service.

Suarez, D.L. 2000. Impact of agriculture on CO_2 as affected by changes in inorganic carbon. In Global Climate and Pedogenic Carbonates, eds. Lal et al., 257-272. Boca Raton:CRC/Lewis.

West L.T., L.R. Drees, L.P. Wilding, and M.C. Rabenhorst. 1988. Differentiation of pedogenic and lithogenic carbonate forms in Texas. *Geoderma* 43:271-287.

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