Quantitative and Qualitative Assessment of Soil Organic Carbon in Native and Cropland Soils in California

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Summary

Irrigation in semi-arid regions can alter soil carbon (C) sequestration processes compared to those of native soils. Towards understanding the effect of these altered processes, we studied the soil C dynamics of two soils from major irrigated agriculture regions of California (the San Joaquin Valley and the Imperial Valley). Soils were sampled from selected native and cultivated fields to provide a time spanning almost a century of irrigated cultivation. Field soil samples were analyzed for total soil C and soil inorganic C as carbonate (SIC). Soil organic carbon (SOC) was then calculated from the measured data. Results showed that the SOC stock increased above that stored in the native soil after five decades of irrigated cultivation. SIC inventory showed opposing trends within the top meter of the two studied soils. In the San Joaquin Valley, SIC decreased over a 55-year period, while in the Imperial Valley SIC increased after 85 years of irrigated agriculture and appears to represent a significant form of sequestered soil C. Our results indicate that long-term irrigated cultivation can significantly increase SOC due primarily to increased SOC added to below the 10-cm soil depth, while significant increases in SIC may be partially due to the conversion of increased soil CO_2 to carbonates under a regime of Colorado River irrigation water. Thus, when considering carbon sequestration in irrigated agriculture in semi-arid regions, it is important to determine both SOC and SIC contents.

Introduction

The largest terrestrial pool of carbon (C) resides within the soil (Schlesinger 1999; Swift 2001), and those factors that affect its retention and release also influence atmospheric CO_2 levels (Kirschbaum 2000; Amundson 2001; Rustad et al. 2001). Worldwide, conversion of native soils to cultivation has resulted in significant loss of soil C from chemical and biological decomposition of soil organic carbon (SOC), as well as from erosion by wind and water (Davidson and Ackerman 1993). However, in carefully managed croplands, soil C sequestration can be substantial and represents a potentially constructive measure for mitigating the rise of atmospheric CO_2 levels (Swift 2001). Processes that sequester soil C include humification of organic matter (OM), formation of organo-mineral aggregates, incorporation of OM beneath the plow zone, and addition of deep root residues (Bruce et al. 1999; Jobbagy and Jackson 2000), as well as precipitation of carbonates as soil inorganic carbon (SIC) (Amundson and Lund 1987).

Irrigation of arid and semi-arid croplands dramatically alters soil-forming processes that are important to C sequestration and release compared to those of native soils. Irrigation, along with

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other agricultural management practices such as tillage, fertilization, water management, and crop rotation, can alter three of the five predominant soil forming factors (Jenny 1941), including (1) climate, as effective precipitation is greatly increased; (2) organisms, including change in vegetation, as sparse shrublands are converted to fields of annual and bi-annual plants, and bioturbation, as the soil undergoes frequent tillage and compaction with heavy machinery; and (3) relief or topography, as land is leveled to promote efficient irrigation, often to an exact tolerance using lasers. Changes in climate and vegetation should add soil organic matter (SOM) through additions of crop residue, increased root mass and organic amendments. The change in topography and tillage in the irrigated system can negatively affect soil C, as SOM is mixed and opened up to processes of oxidation and microbial decomposition, and as topsoil and associated SOC is removed.

Worldwide, irrigated cropland exceeds 271 million ha and additional land is expected to be converted to irrigated cultivation as the world's population continues to grow and marginal lands are reclaimed for agriculture (Bruinsma 2003). However, few field data are available for quantifying the impact of irrigated cultivation on dynamic transformations of soil C (Lal et al. 1999; Follet 2001). Both losses (Rounsevell et al. 1999; West and Marland 2002; Wu et al., 2003) and additions (Lal et al., 1999; 2000a,b; Smith et al., 2000a,b; Uri, 2001; Vleeshouwers and Verhagen 2002; West and Marland 2002; Entry et al. 2004a) of soil C have been observed in lands after being converted to irrigated croplands. For example, irrigated agriculture has been shown to increase SOC by 1.66 Mg ha^{-1} within the top 30 cm of soil after 15 years (Lueking and Schepers 1985). Alternatively, there is concern that irrigated cultivation can accelerate the transfer of C from soil to atmosphere by improving environmental conditions for microbial SOC decomposition (Schlesinger 1999).

On a global average, C stored in cultivated shallow, saline, sodic, and arid soils was considerably lower than that of the native soils (Paustian et al. 1998). However, soil C increases linearly with increased additions of crop residues and root OM (Paustian et al. 1998), suggesting that irrigated cultivation will increase soil C with time (Lal et al. 1998; Follett 2001). It is typical that SOC generally declines at the beginning, approaches a steady state in 25-50 years, and shows an evident increase in about 50 years after conversion of native soil to agricultural land (Swift 2001; Janzen et al. 1998; Lal et al. 1998). This suggests that time is an important factor for C sequestration in irrigated cropland.

The objective of this study was to assess the effect of irrigated cultivation on soil C sequestration and dynamics in two California soils over known lengths of time. California's arid and semi-arid croplands are among the most productive agricultural regions in the world. With a long growing season suitable for diverse commodities, crop production is limited only by the availability of water. Since the beginning of the 19th century, California's irrigated cropland has increased from about half a million (Hundley 2001) to 3.65 million ha, and now represents about 95% of the total cultivated land in the state (CADWR 1998). With different regions of the state receiving irrigation water at different times over the last century, California's croplands present an excellent opportunity to investigate time as a factor in soil C sequestration with irrigated cultivation.

Materials and Methods

Field Sites and Soil Sampling

Representative soil series from two agricultural regions within California, the San Joaquin Valley (SJV) and the Imperial Valley (IMP), were selected for this study (*table 1*). The two soils were chosen to provide a time series – or chronosequence – covering change from the native soil to nearly a century of irrigated cultivation.

Table 1. *Site information for the two irrigated cultivation sites in California.*

	San Joaquin Valley	Imperial Valley
Site Characteristics		
Nearest Municipality	Wasco, CA	Holtville, CA
Duration of Irrigated cultivation	25 to 55 years	85 to 90 years
Main Crops	Alfalfa, wheat, cotton, corn, sugar beets	Alfalfa, wheat, corn, sugar beets
Irrigation Water	Well water	Colorado River
Average pH	7.2	7.9
Salinity (EC) †	0.19 dS m^{-1}	1.2 dS m^{-1}
Bicarbonate (mg L^{-1})	73.2	190
Mean Annual Precipitation	132- mm	65 mm
Mean Annual Temperature	18ºC	22ºC
Mean daily ET	4.2 mm	5.1 mm
Soil Characteristics		
Soil order	Entisol	Entisol
Soil series	Garces (Fine-loamy, mixed, superactive, calcareous, thermic Sodic Torriarents)	Imperial (Fine, smectitic, calcareous, hyperthermic Vertic Torrifluvent)
Parent Material	Sierra Nevada alluvial fan granitic sediments	Flood plain deposits from ancient Colorado River
Texture		
Surface (0-25 cm)	Loam	Silt clay
Subsurface (50-100 cm)	Loam	Silt clay loam
Clay Content (by weight)		
Surface (0-25 cm)	15 - 25%	34 - 42%
Subsurface (50-100 cm)	14 - 21%	24 - 36%
Soil pH	8.0 - 8.2 (0 - 20 cm) 9.2 (20 - 100 cm)	8.2 – 8.4 (0 - 100 cm)

† Estimated from cation and anion concentrations in water.

The soils of both cropland sites are classified as Entisols (U.S. Department of Agriculture, 1981, 1988). They have similar effective climates (due to the use of irrigation to provide sufficient water for optimum plant growth), topography (due to leveling of fields), and vegetation (*table 1*), but the Imperial Valley soil has (1) a longer time under irrigated cultivation, (2) soil texture of less sand and more clay, (3) higher carbonate concentration in the native soil, and (4) higher salt concentration of the irrigation water than the San Joaquin Valley soil. The two soils have similar pH values in the top 20-cm (8.0 to 8.4, *table 1*). However, the pH of the IMP subsoil (20-100 cm) is lower (8.0-8.2) than that of the SJV subsoil (9.2, see *table 1*).

San Joaquin Valley

Field selection within the SJV was made based on earlier work of Amundson and Lund (1987). In their study, samples were collected from the Garces soil (Fine-loamy, mixed, superactive, thermic Typic Natrargid), as the native soil, from a location near Wasco, California. They selected four additional fields in 1982 based on repeat aerial photographs to represent various times of conversion to cultivated cropland (Amundson and Lund 1987). All the soil samples from the San Joaquin Valley are hereafter referred to as the SJV soils.

Samples for this study were collected from three of the cultivated fields studied by Amundson and Lund (1987). A fourth field was selected that has been under cultivation for 55 years (Blake Sandon, personal communication). This site was selected based on conversations with a descendant of a longtime farming family in the region, and the length of cultivation was confirmed by aerial photos. At the time of sampling for this current study (2002), the selected fields had been under irrigated cultivation for 25, 30, 45, and 55 years.

Additionally, a fifth site, covered by wildland vegetation, was sampled to represent the untilled Garces sandy loam soil (the 0-year field). This site was located approximately 0.5 km from where Amundson and Lund (1987) took their native soil samples, and approximately 1 km away from where the Kern County type soil for the Garces series was described (U.S. Department of Agriculture 1988). Local University of California County Extension Advisors and landowners were queried to ascertain that our 0-year soil had never been under cultivation. Additionally, the soil characteristics that we measured at our native soil site were compared to those reported by Amundson and Lund (1987) for their sampled native soil as well as by the Soil Survey team (U.S. Department of Agriculture 1988) to ensure consistency between the soils sampled as native.

Imperial Valley

Samples of the Imperial silty clay soil (Fine, smectitic, calcareous, hyperthermic Vertic Torrifluvent) were collected from sites near Holtville, California, in the Imperial Valley. Nearly all land suitable for farming in the Imperial Valley was converted to irrigated agriculture in the early 1900s, after Colorado River water was delivered through a series of canals. The locations sampled for this study have been under irrigated cultivation for 85 years and for 90 years. Additionally, a third site was chosen to represent the native Imperial soil (the 0-year soil). This set of samples is referred to hereafter as the IMP soils.

Soil Sampling

At each field site (San Joaquin Valley and Imperial Valley), samples for the upper two layers (0-10 and 10-25 cm depth) were taken by hand in open pits while the lower two layers (25-60 and 60-100 cm depth) were taken using a sampling tube (2.5 cm diameter) from five locations (replicates) separated by 10 m from each other. A total of 100 samples (5 treatments represent 5 different years of irrigated cultivation x 5 replicates x 4 depths) were collected in San Joaquin Valley and 60 samples (3 treatments x 5 replicates x 4 depths) were collected in the Imperial Valley in March 2003. Additionally, undisturbed soil samples were collected using 5-cm long cores (of 5.4-cm diameter) to determine soil bulk density with depth.

Laboratory Procedures

All bulk samples were air-dried, ground to pass a 2-mm sieve, and then stored for chemical and physical analyses. Soil textures for the four layers to the 100-cm depth were determined by the hydrometer method (Gee and Bauder 1982) using two replicate samples from each site.

The air-dried, sieved bulk soil samples were further ground to pass a 0.2-mm sieve to determine the total soil C concentration by dry combustion of 20-mg aliquots of the samples using a Carlo-Erba C and N Analyzer (Reeves et al. 1997). The SIC concentration as calcium carbonate equivalent (CCE) was determined by the manometer method (Nelson 1982). The SOC concentration is reported as the difference between the measured total soil C and the measured SIC.

Calculations and Statistical Analysis

In this study, values of total soil C, SOC, and SIC are reported as concentrations based on dry soil mass (g kg^{-1}) and as stock (kg m^{-2}) within 1-m soil depth. Average soil C concentrations to the 1-m depth were determined as weighted averages. To do so, the C concentrations for each of the four sampled intervals were multiplied by their respective depths (in cm), summed, and divided by 100. Carbon stock for each sampled interval was determined by multiplying the respective C concentration by the measured soil bulk density. The total C stock (to the 1-meter depth) of a profile was calculated by summing the C stocks in the four sampling intervals.

After performing the normality test, one-way analysis of variances (ANOVA) was performed on total C, SIC, and SOC among the treatments (i.e., time in year) in each of the two field sites (SJV and IMP) to determine the effect of irrigated cultivation on C concentration and stock. The PROC ANOVA of SAS statistical software (SAS Institute Inc.) was used to test global F-values, and when the F-value was significant (P-value ≤ 0.05), the treatment means were separated by least significant difference (LSD).

To utilize the data from the two study sites (SJV and IMP) to assess the time effect on C sequestration, the C concentrations and stock of the cultivated fields (c) were divided by their respective values of the native soils (c_n). The dimensionless ratio (c/c_n) of 1 means that cultivation does not change C concentration, while a ratio less than 1 or greater than 1 implies that cultivation decreases or increases, respectively, soil C concentration compared to the sampled native soils.

Results and Discussion

Soil Carbon Dynamics Over Time of Irrigation

The 0-year, or native soils, from SJV and IMP differed three-fold in their total soil C stock (*table 2*). This large difference resulted from differing amounts of carbonates (SIC) measured in the native soils (*fig. 1, table 2*). Measured SIC stock in the IMP native soil (16.55 kg m^{-2}) was seven times greater than that measured in the SJV native soil (2.58 kg m^{-2}). These differences result from unique site characteristics, such as parent material and surface water chemistry, which affect the dynamics of SIC. In contrast, SOC stock to the 1-meter depth within the two native soils are very similar in amount (3.38 kg m^{-2} for the SJV soils and 2.98 kg m^{-2} for the IMP soils). These similarities result from similar site characteristics important to SOC dynamics such as climate and vegetation, and allow direct comparison of SOC dynamics between the two studied sites.

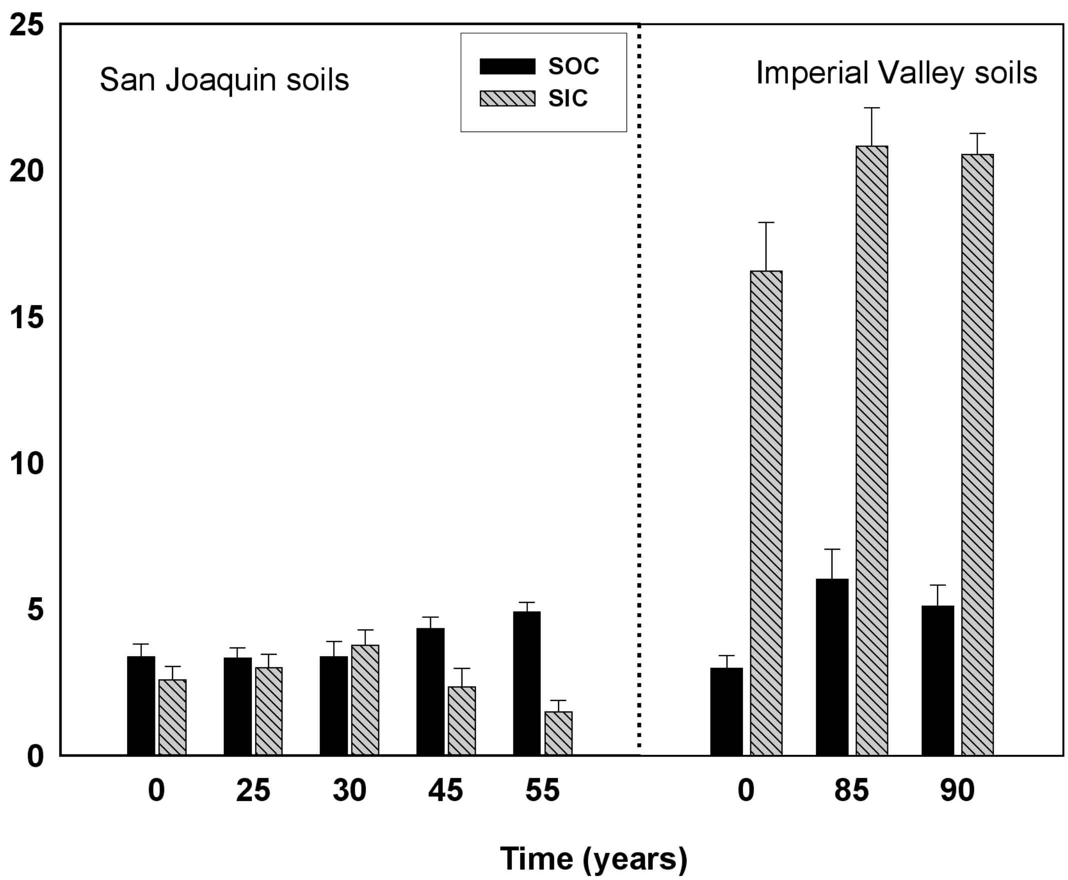

Figure 1. Soil inorganic carbon (SIC) and soil organic carbon (SOC) stock changes over time of irrigated cultivation. Error bars are one standard deviation.

Table 2. *Soil C concentrations (g kg^{-1}) and C stocks of the top 1-m profile (kg m^{-2}) for irrigated and native sites from two of California's major agricultural regions.*

	Soil carbon concentrations† (g kg^{-1})			Soil carbon stock in the top 1m (kg m^{-2})		
	Total	Inorganic	Organic	Total	Inorganic	Organic
	San Joaquin Valley: Garces soil					
Native	5.12b	2.34b	2.78bc	5.97b	2.58bc	3.38c
Irrigated cultivation						
25 yr.	5.15b	2.45b	2.70c	6.33ab	3.00b	3.33c
30 yr.	6.98a	4.11a	2.87bc	7.15a	3.78a	3.37c
45 yr.	4.83b	1.63bc	3.20b	6.66ab	2.33c	4.33b
55 yr.	4.91b	1.03c	3.88a	6.40ab	1.49d	4.91a
$LSD_{0.05}$	1.26	1.21	0.46	0.86	0.67	0.55
	Imperial Valley: Imperial soil					
Native	16.01b	13.53b	2.48b	19.52b	16.55b	2.98b
Irrigated Cultivation						
85 yr.	19.12a	14.80ab	4.33a	26.84a	20.82a	6.02a
90 yr.	19.96a	16.17a	3.80a	25.63a	20.53a	5.09a
$LSD_{0.05}$	--‡	--	--	2.18	1.78	1.07

† Soil carbon concentrations (g kg^{-1}) are depth-weighted averages of four layers.
‡ A single LSD value is not reported due to different sample sizes. There were n = 6 samples for Imperial native soil, whereas there were n = 5 for the two irrigated cultivation treatments.

In the IMP site, where fields have been tilled for at least 85 years, significant increases in both SIC and SOC (*fig. 1*) resulted in an increase in total soil C under irrigated cultivation (*table 2*). In these irrigated cropland soils, increased SIC stock due to carbonate precipitation represented an important mechanism for sequestering total soil C (Margaritz and Amiel 1981; Amundson and Lund 1987).

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Table 3. *Soil physical characteristics and carbon concentration by depth for irrigated and native sites of the two test soils.*

Time	Depth (cm)	Bulk density ($kg\ m^{-3}$)		Texture (<2mm)	Total C ($g\ kg^{-1}$)		Inorganic C ($g\ kg^{-1}$)		Organic C ($g\ kg^{-1}$)	
San Joaquin Valley: Garces soil (Fine-loamy, mixed, superactive, thermic Typic Natrargid)										
Native soil										
0 yr.	0-10	1.43	(0.03)	sil	9.25	(2.23)	1.12	(1.23)	8.14	(1.69)
	10-25	1.26	(0.08)	sicl	6.81	(0.47)	3.43	(0.68)	3.37	(0.49)
	25-60	0.98	(0.13)	sic	4.97	(0.37)	2.87	(0.33)	2.10	(0.55)
	60-100	1.19	(0.06)	l	3.59	(0.51)	1.78	(0.53)	1.81	(0.39)
Irrigated cultivation										
25 yr.	0-10	1.16	(0.07)	l	7.14	(0.18)	0.92	(0.27)	6.22	(0.30)
	10-25	1.24	(0.06)	l	6.43	(0.17)	0.91	(0.33)	5.52	(0.22)
	25-60	1.29	(0.05)	l	4.90	(0.44)	2.80	(0.76)	2.10	(0.46)
	60-100	1.20	(0.09)	sil	4.39	(0.78)	3.09	(0.64)	1.30	(0.39)
30 yr.	0-10	1.16	(0.07)	l	8.20	(0.11)	1.42	(0.15)	6.77	(0.16)
	10-25	1.17	(0.10)	l	7.64	(0.23)	1.43	(0.36)	6.21	(0.25)
	25-60	1.16	(0.07)	l	6.37	(2.06)	4.12	(1.75)	2.24	(0.86)
	60-100	1.12	(0.06)	l	6.97	(4.58)	5.78	(4.60)	1.20	(0.52)
45 yr.	0-10	1.40	(0.04)	l	7.78	(0.62)	0.42	(0.65)	7.36	(0.87)
	10-25	1.43	(0.10)	l	5.57	(0.33)	0.45	(0.12)	5.12	(0.43)
	25-60	1.32	(0.10)	l	5.49	(0.68)	2.34	(0.74)	3.16	(0.40)
	60-100	1.44	(0.07)	l	3.25	(0.81)	1.77	(1.06)	1.48	(0.36)
55 yr.	0-10	1.06	(0.09)	l	8.92	(1.09)	0.18	(0.07)	8.74	(1.08)
	10-25	1.19	(0.09)	l	8.17	(0.45)	0.19	(0.08)	7.98	(0.49)
	25-60	1.38	(0.07)	l	4.98	(0.61)	1.21	(0.30)	3.78	(0.40)
	60-100	1.52	(0.12)	l	2.63	(0.85)	1.41	(0.57)	1.22	(0.47)

Table 3 (continued).

Time	Depth (cm)	Bulk density ($kg\ m^{-3}$)		Texture (<2 mm)	Total C ($g\ kg^{-1}$)		Inorganic C ($g\ kg^{-1}$)		Organic C ($g\ kg^{-1}$)	
				Imperial Valley: Imperial soil (Fine, smectitic, calcareous, hyperthermic Vertic Torrifluvent)						
Native soil										
0 yr.	0-10	0.98	(0.11)	sicl	17.6	(1.09)	13.0	(0.62)	4.62	(1.42)
	10-25	1.13	(0.07)	sic	16.6	(0.70)	13.2	(0.69)	3.43	(0.36)
	25-60	1.35	(0.06)	cl	15.5	(1.28)	13.2	(1.11)	2.28	(0.54)
	60-100	1.28	(0.03)	sicl	16.1	(4.14)	14.2	(3.66)	1.91	(0.69)
Irrigated cultivation										
85 yr.	0-10	1.22	(0.06)	sic	22.8	(0.47)	14.6	(0.24)	8.15	(0.65)
	10-25	1.45	(0.02)	sic	22.2	(1.21)	14.4	(0.66)	7.73	(1.71)
	25-60	1.42	(0.03)	sic	19.3	(1.00)	14.9	(0.52)	4.42	(1.20)
	60-100	1.43	(0.19)	sicl	16.9	(2.78)	14.9	(2.36)	2.02	(0.44)
90 yr.	0-10	1.23	(0.02)	sic	21.4	(0.27)	13.9	(0.81)	7.50	(0.59)
	10-25	1.12	(0.03)	sic	21.4	(0.26)	13.9	(1.10)	7.48	(1.11)
	25-60	1.29	(0.02)	sic	20.4	(0.18)	16.2	(1.28)	4.14	(1.22)
	60-100	1.34	(0.20)	sil	19.0	(0.16)	17.0	(0.44)	1.94	(0.50)

In the SJV site, total C stock among the treatments was not significantly different (*table 2*). In the two older fields cultivated longer than 45 years, SOC stocks increased significantly, while SIC stocks decreased in the 45-year treatment. In the two younger SJV fields, SIC stocks increased slightly but significantly, while SOC stocks remained the same (*table 2*). This result shows that initially, SOC stock to 1-m depth in the SJV site showed no change. As much as five decades of irrigated cultivation was required in these soils to show an increase in SOC stock above that of the native soil (*table 2, fig. 1*). This time period is similar to that observed by others in non-irrigated cropland (Paustian et al. 1998). These results also indicate that it is essential to measure the SIC stock of irrigated arid lands when studying SOC dynamics.

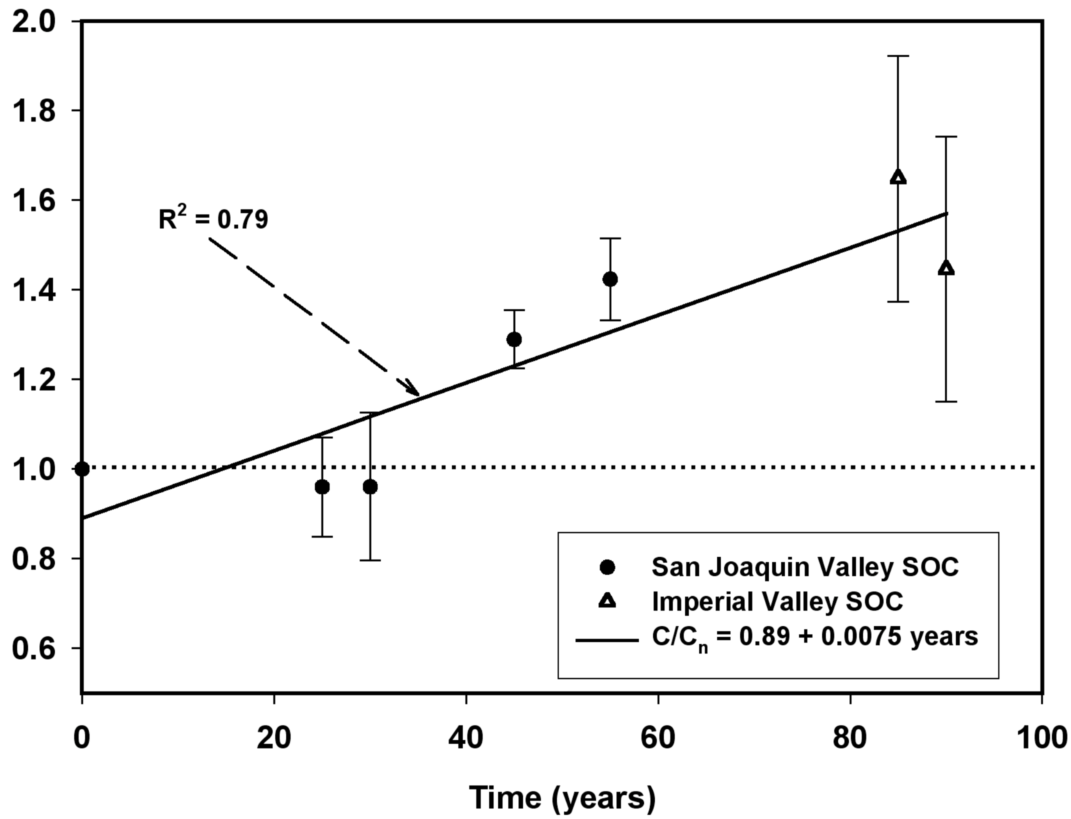

Figure 2. Normalized soil organic carbon (SOC) stock trends over time of irrigated cultivation. Carbon stock data to 1-meter depth from both cropland soils (c) are presented with these data normalized to the carbon stock of their corresponding native soil (c_n). Symbols are measured data with error bar.

The time series of this study does not form a true soil chronosequence because of the inherent differences between the two studied sites. However, the similarities in the SOC character of the native soils suggest that the entire nine decades of the time series could be used to consider rates of SOC accumulation under irrigated cultivation. To do so, we normalized the SOC concentration data as described in the methods section and graphed them in figure 2. Over time, irrigated cropland SOC stocks accumulated at a rate of about 0.75% of that of the native soil per year if the entire nine decades of this study is considered (r^2 = 0.79, *fig. 2*).

It is typical that cultivated soils have a lower bulk density than their respective native soils, which might affect C stock estimation in soils (Ellert and Bettany 1995). However, this effect was not considered in our study. Due to the low C content beyond the 1-m depth, we anticipated that this effect was insignificant.

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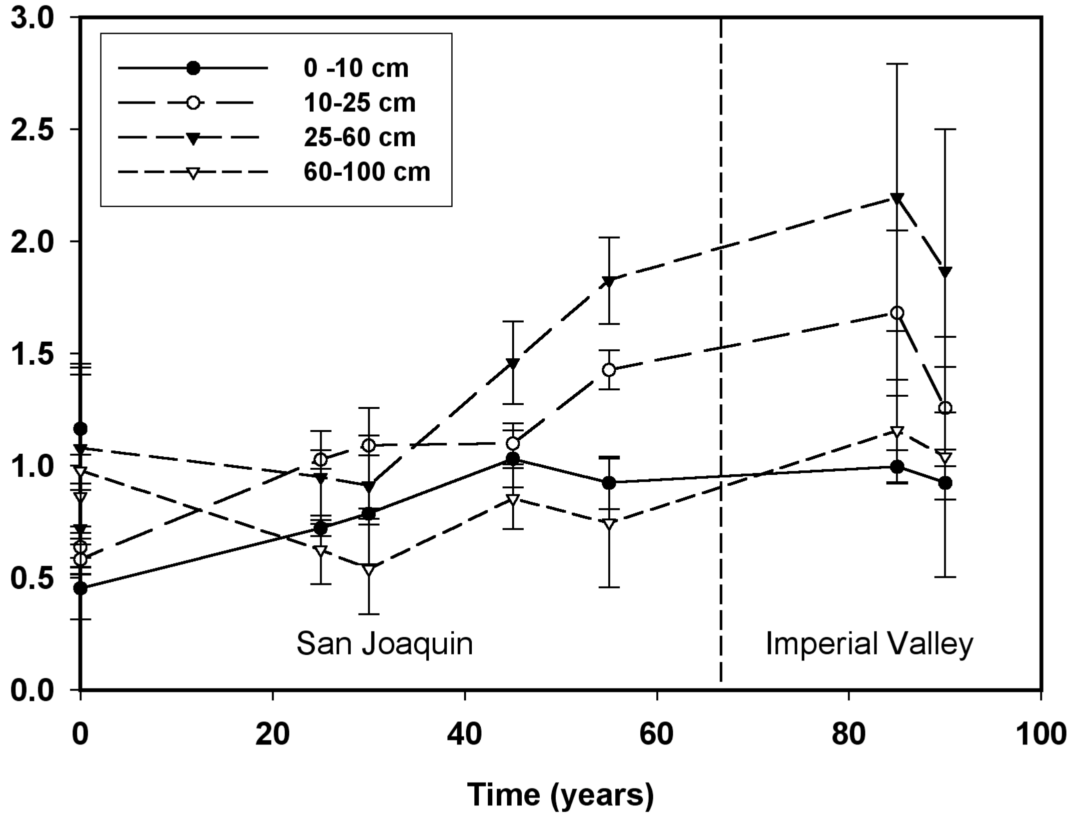

Figure 3. SOC stock trends by depth increments for the two study sites of irrigated cropland in arid California.

SOC Dynamics With Depth Under Irrigation

The rate of SOC additions is most rapid within the 25 to 60 cm soil depth (*fig. 3*). This may reflect the more recalcitrant nature of root carbon additions (Rasse et al. 2005) at this depth where irrigated crop roots are much denser than those of native shrubs (Jobbagy and Jackson 2000). Here, below the plow layer where OM is less prone to decomposition (Lal and Kimble 1997), SOC stock increased 103% and 153%, respectively, above that of the native SJV soil (0.72 kg m^{-2}) after 45 and 55 years (1.46 and 1.83 kg m^{-2}, respectively, for the 45 and 55 year) of irrigated cultivation and 104% and 73%, respectively, above that of the native IMP soil (1.07 kg m^{-2}) after 85 and 95 years of irrigated cultivation (2.20 and 1.87 kg m^{-2}, respectively for the 85 and 95 year).

The highest concentration of SOC is found at the surface of the studied soils (*table 3*). Over time, the lower depth to which high SOC concentration is found increases from 10 cm under native shrubland to 25 cm under irrigated cultivation (*table 3*). We suggest that this trend towards uniformity of SOC concentration within the top 25 cm of irrigated fields (*table 3*) results from mixing and incorporation of near surface OM into the plow zone during disking (Nguyen and Goh 1992; Murata et al. 1995). Disking usually extends to at least a 30-cm depth and affects the dynamics of SOC between both the 0 to 10 and the 10 to 25-cm depths as crop root and shoot residues are incorporated into the soil. SOC significantly increases in the 10 to 25-cm depth of the agricultural fields above that of the native shrublands (*fig. 3; table 3*) at a rate nearly identical to that within the top 10 cm of soil (*fig. 3*). As a result, the 10 to 25-cm soil depth becomes a fast SOC accumulation zone (*fig. 3*) and represents an important zone of SOC accumulation under conditions of irrigated cultivation. Here we measured values of SOC stock in the cropland soils that had increased 133% above those of the native soil within 55 years and 116% in 90 years (*fig. 3*). This suggests that SOC can be sequestered in the plow layer of irrigated cropland soils over time of cultivation.

The SOC stock in the top 10-cm of the SJV and IMP sites shows a slight increase above that of the native soils after conversion to irrigated cropland (*fig. 3*). At soil depth of 60 to 100 cm, below the predominant region of crop roots (Jobbagy and Jackson 2000), SOC shows little change over time (*fig. 3*).

Changes in Soil Physical Characteristics Over Time Under Cultivation

Soil physical characteristics such as soil texture, permeability, and structure are important in total soil C sequestration. Changes to native soil during conversion to irrigated cultivation are usually substantial. For the SJV site, this conversion resulted in loss of soil structure, homogenization of soil texture to at least a one-meter depth, and increased soil bulk density (U.S. Department of Agriculture 2003) (*table 3*). The soil texture of the native SJV soil shows increased clay with depth, reflective of strongly developed natric horizons within 50 cm of the surface (U.S. Department of Agriculture 1988). In contrast, the soil textures of almost exclusively loam to the 1-m depth of the cropland SJV soils reflect the deep ripping and mixing of the soil upon its conversion to cultivation (U.S. Department of Agriculture 2003). The 55-year-old field has loam texture to the 25-cm depth, below which is seen increased clay content which may be evidence of translocated clay over time of cultivation (Graham and Wood 1991). Mixing and homogenization of the IMP soil is also evident in table 3. Here, cropland soils have silty clay textures to the 60-cm depth, having lost the variability evident in the native soil texture.

A soil physical characteristic important to sequestration of SOC is the amount of clay in the fine earth fraction (<2 mm). The amount of SOC rose in each soil since its conversion to irrigated agriculture from the native soil in direct relation ($r^2 = 0.92$) to the amount of clay measured in the soil (*fig. 4*). Similar relations have been observed in other studies to a depth of 20-cm (Burke et al. 1989; Hevia et al. 2003), while in this study the correlation has been seen to the depth of 100 cm. These results suggest that finer-textured soils represent potential sites for increased sequestration of SOC (Burke et al. 1989) during irrigated cultivation. However, with such a clear correlation between clay content and SOC stock (*fig. 4*), it could prove valuable to investigate the effects of irrigated cultivation over decades on soil clay increase (Graham and Wood 1991).

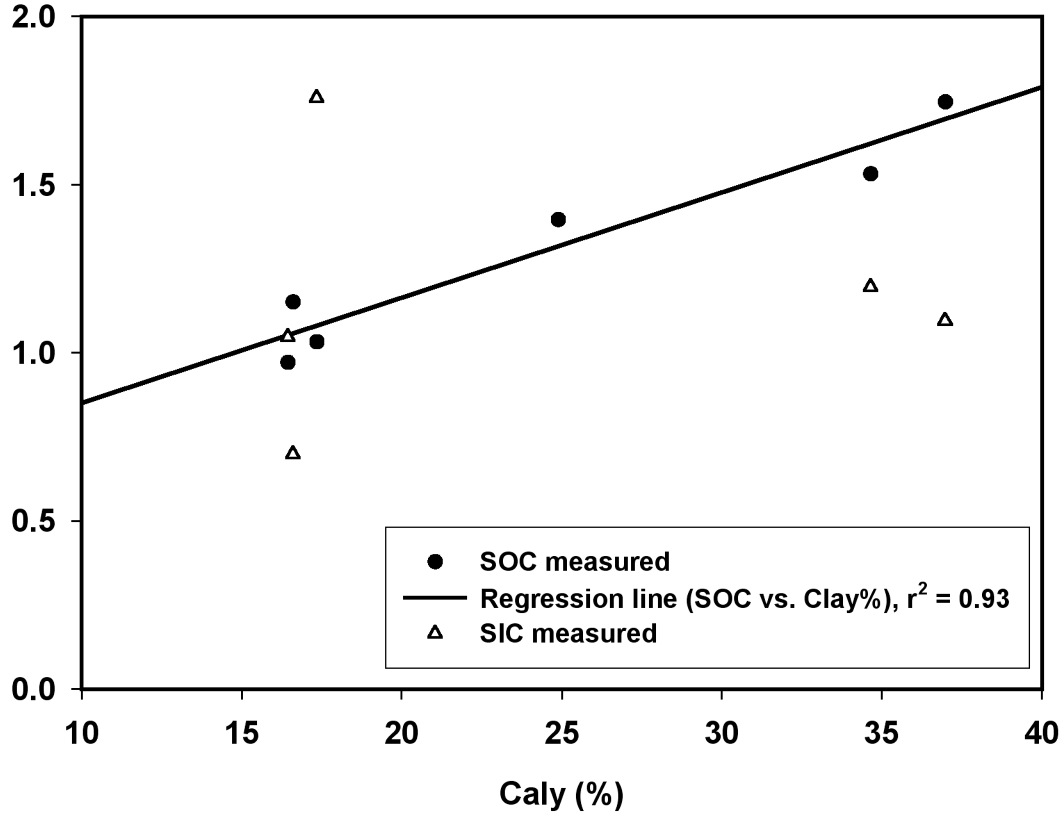

Figure 4. Mean values of SOC concentration of the test soils for the top one meter of soil normalized to those of the native soils for SOC in relation to weighted mean clay content for the top one meter of soil (c/c_n = 0.0313 Clay% + 0.5378; $p < 0.01$). Soils with mean clay content less than 30% represent the Garces soil samples from the San Joaquin Valley, while those greater than 30% represent the Imperial soil samples.

SIC Dynamics With Depth Under Irrigation

Significant amounts of SIC accumulated in the IMP soil profiles over long-term periods of irrigated cultivation. SIC precipitated in the deeper soil horizons (*table 3*) provides greater potential for carbon sequestration beyond SOC sequestered in nearer surface soil less than 60-cm depth. This trend agrees with the work of Entry et al. (2004b, c), which indicates that irrigation increases SIC in agricultural soils of arid and semi-arid regions. In these regions, calcium content in the soils is often elevated compared to temperate regions due to calcium-rich parent material and low rainfall. Carbonate formation in soil solution is usually controlled by equilibrium reactions in the solid phase carbonate minerals and gaseous phase CO_2 (Levy 1980; Robbins 1985). In this manner, the CO_2 derived from the decomposition of organic matter and plant respiration will dissolve in the soil solution to form carbonate species. These in turn can precipitate with the calcium ions often supplied by irrigation water when the conditions are favorable (Duke 1992).

Irrigation water chemistry plays an important role in SIC accumulation in cultivated fields if it contains significant amounts of calcium and/or carbonate and if leaching is not sufficient. In the SJV soils, the irrigation water generally has low salinity, averaging 0.05 to 0.5 dS m^{-1} for water from various sources. Under the normal leaching requirement, inorganic C precipitation as $CaCO_3$ in the SJV soils is expected to be insignificant. However, even in these soils, SIC has accumulated at depths greater than 150 cm under the influence of irrigated cultivation (U.S. Department of Agriculture 2003).

In the Imperial Valley, irrigation water is directly from the Colorado River, which averages 1.2 dS m^{-1} with major dissolved ions of calcium, sulfate and chloride. The increased SIC in the IMP cultivated soils, in comparison to the native soil, appears to be primarily due to the precipitation of calcium carbonate ($CaCO_3$). In this process the carbonate ion must come from the CO_2 in the soil atmosphere. In turn, the CO_2 in the soil is the result of organic matter decomposition and plant respiration. This suggests that the SIC accumulating in these soils has sequestered some of the C initially added as SOM during irrigated cultivation.

Conclusions

The dynamics of SOC sequestration within irrigated cropland soils are similar at both studied sites even though their native soils differed in total soil C. However, the SOC additions did not significantly increase above those of the native soil until after five decades of irrigated cultivation.

The predominant source of increased SOC stock over time appears to be the addition of crop root C. SOC from crop roots is more resistant to decomposition than that of above ground shoot residue (Rasse et al. 2005). Within these two soils, the fastest rate of SOC sequestration occurred in the 10- to 25-cm and 25- to 60-cm depth, where crop roots are dense, especially in comparison to native shrubs (Jobbagy and Jackson 2000). The abandonment of deep disking greater than 30-cm depths after the initial conversion of native soil to cropland is suggested as a means of retaining SOC within these irrigated soils.

The dynamics of SIC sequestration as carbonate precipitation differed between the two studied sites. SIC was the predominant determinant of total soil C in the studied soils, and processes important in its precipitation need to be considered when studying arid land that has been converted to irrigated cultivation. Our results indicate that, in addition to the carbonate content of the parent material, the chemical nature of the applied irrigation water is important in the retention and addition of SIC.

The substantial changes in soil physical properties that occur during conversion of native soils to irrigated cultivation can affect processes of total soil C sequestration. Our data indicate that soil texture is related to increased SOC stock, and cultivation processes that promote erosion and reduction in soil clay content will effectively reduce SOC.

References

Amundson, R.G. 2001. The carbon budget in soils. *Annual Review of Earth and Planetary Science* 29:535-562.

Amundson, R.G., and L.J. Lund. 1985. Changes in the chemical and physical properties of a reclaimed saline-sodic soil in the San Joaquin Valley of California. *Soil Science* 140: 213-222.

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

Bruce, J.P., M. Frome, E. Haites, H. Janzen, and R. Lal. 1999. Carbon sequestration in soils. *Journal of Soil and Water Conservation* 54:382-389.

Bruinsma, J. 2003. *World agriculture: Towards 2015/2030, an FAO perspective*. London: Earthscan Publications Ltd., 432 pp.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach, and D.S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. *Soil Science Society of America Journal* 53:800-805.

CADWR (California Department of Water Resource). 1998. California Water Plan Update Bulletin 160-98. Sacramento, CA.

Davidson, E.A., and I.L. Ackerman. 1993. Changes in soil C inventories following cultivation of previously untilled soils. *Biogeochemistry* 20:161-193.

Duke, H.R. 1992. Water temperature fluctuations and effect on irrigation infiltration. *Transcripts of the American Society of Agricultural and Biological Engineers* 35:193–199.

Ellert, B.H., and J.R. Bettaby. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science* 75: 529-538.

Entry, J.A., R.E. Sojka, and G.E. Shewmaker. 2004a. Management of irrigated agriculture to increase organic carbon storage in soils. *Soil Science Society of America Journal* 66:1957-1964.

Entry, J.A., R.E. Sojka, and G.E. Shewmaker. 2004b. Irrigation increases inorganic carbon in agricultural soils. *Environmental Management* 33:S309-S317.

Entry, J.A., J.J. Fuhrmann, R.E. Sojka, and G.E. Shewmaker. 2004c. Influence of irrigated agriculture on soil C and microbial community structure. *Environmental Management* 33: S363-S373.

Follett, R.F. 2001. Soil management concepts and carbon sequestration zin cropland soils. *Soil and Tillage Research* 6:77-92.

Gee, G.W., and J.W. Bauder. 1982. Particle-size analysis. p. 383-411. In *Methods of soil analysis: Part 1. Physical and mineralogical methods*, ed. A. Klute, Agronomy Monographs 9. 2nd ed. Madison, WI: ASA and SSSA.

Graham, R.C., and H. Wood. 1991. Morphologic development and clay redistribution in lysimeter soils under chaparral and pine. *Soil Science Society of America Journal* 55:1638-1646.

Hevia, G.G., D.E. Buschiazzo, E.N. Hepper, A.M. Urioste, and E.L. Antón. 2003. Organic matter in size fractions of soils of the semiarid Argentina. Effect of climate, soil texture and management. *Geoderma*. 116:265-277.

Hundley, N. Jr. 2001. *The Great Thirsty-Californians and Water: A History*. Revised Ed. Berkeley: University of California Press.

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. *Soil Tillage Research* 47:181-195.

Jenny, H. 1941. Factors of Soil Formation: a System of Quantitative Pedology. 281 pp. McGraw-Hill, New York.

Jobbagy, E.G. and R.B. Jackson. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10:423-236.

Kirschbaum, M.U.F. 2000. Will changes in soil organic carbon act as a positive or negative feedback on global warming? *Biogeochemistry* 48:21-51.

Lal, R. 2000a. Carbon sequestration in drylands. *Annals of Arid Zone* 39:1-10.

Lal, R. 2000b. Land use and cropping system effects on restoring soil carbon pool of degraded alfisols in western Nigeria. *In Global Climate Change and Tropical Ecosystems*, eds. R. Lal, J. Kimble, and B. Stewart, 157-165, Oxford: Gergamon.

Lal, R., and J.M. Kimble. 1997. Conservation tillage for carbon sequestration. *Nutrient Cycling in Agroecosystems* 49:243–253.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1998. *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect*, 128 pp., Chelsea, MI: Ann Arbor Press.

Lal, R., R.F. Follett, J.M. Kimble, and C.V. Cole. 1999. Managing U.S. cropland to sequester carbon in soil. *Journal of Soil and Water Conservation* 54:374-381.

Levy, R. 1980. Precipitation of carbonates in soils in contact with waters unsaturated or oversaturated in respect to calcite. *Journal of Soil Science* 31:41–51.

Lueking, M.A., and J. S. Schepers. 1985. Changes in soil carbon and nitrogen due to irrigation development in Nebraska's sandhill soils. *Soil Science Society of America Journal* 49:626-630.

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

Murata, T., M.L. Nguyen, and K.M. Goh. 1995. The effects of long-term superphosphate application on soil organic matter content and composition from an intensively-managed New Zealand pasture. *European Journal of Soil Science* 46:257–264

Nelson, D.W. 1982. Carbonate and gypsum. In *Methods of Soil Analysis. Part 2. Chemical and microbiological properties*, eds. A.L. Page, R.H. Miller, and D.R. Keeney, Agronomy Monographs 9. 2nd ed., 181-197, Madison, WI: ASA and SSSA.

Nguyen, M.L., and K.M. Goh. 1992. Status and distribution of soil sulphur fractions, total nitrogen and organic carbon in camp and non-camp soils of grazed pastures supplied with long-term superphosphate. *Biology and Fertility of Soils* 14:181–190.

Paustian, K., C.V. Cole, D. Sauerbeck, and N. Sampson. 1998. CO_2 mitigation by agriculture: An overview. *Climatic Change* 40:135-162.

Rasse, D.P., C. Rumpel, and M-F. Dignac. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilization. *Plant and Soil* 269:341-356.

Reeves, M., R. Lal, T. Logan, and J. Sigarăn. 1997. Soil nitrogen and carbon response to maize cropping system, nitrogen source, and tillage. *Soil Science Society of America Journal* 61:387-1392.

Robbins, C.W. 1985. The $CaCO_3$–H_2O system in soils. *Journal Agronomy Science* 14:3–7.

Rounsevell, M.D.A., S.P. Evans, and P. Bullock. 1999. Climate change and agricultural soils: impacts and adaptation. *Climatic Change* 43:683-709.

Rustad, L.E., J.L. Campbell, G.M. Marion, R. Norby, M. Mitchell, A. Hartley, J. Cornelissen, J. Gurevitch, and GCTE-NEWS. 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia* 126: 534-562.

Schlesinger, W.H. 1999. Carbon sequestration in soils. *Science* 284:2095.

Smith, P., R. Milne, D.S. Powlson, J.U. Smith, P. Falloon, and K. Coleman. 2000a. Revised estimates of the carbon mitigation potential of UK agricultural land. *Soil Use and Management* 16:293-295.

Smith, P., R. Milne, D.S. Powlson, J.U. Smith, P. Falloon, and K. Coleman. 2000b. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology* 6:525-539.

Swift, R.S. 2001. Sequestration of carbon by soil. *Soil Science* 166:858-871.

Uri, N.D. 2001. The potential impact of conservation practices in US agriculture on global climate change. *Journal of Sustainable Agriculture* 18:109-131.

U.S. Department of Agriculture. 1981. Soil Survey of Imperial County, California, Imperial Valley Area. 112 pp., Washington, DC: U.S. Government Printing Office.

U.S. Department of Agriculture. 1988. Soil Survey of Kern County, California, Northwestern Part. 304 pp., Washington, DC :U.S. Government Printing Office.

U.S. Department of Agriculture. 2003. Soil Survey of Tulare County, California, Western Part. 278 pp., Washington, DC: U.S. Government Printing Office.

Vleeshouwers, L.M., and A. Verhagen. 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. *Global Change Biology* 8:519-530.

West, T.O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. *Agriculture, Ecosystems and Environment* 91:217-232.

Wu, H.B., Z.T. Guo, and C.H. Peng. 2003. Land use induced changes of organic carbon storage in soils of China. *Global Change Biology* 9:305-315.

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