DOI: 10.1007/s00267-003-9140-3

Irrigation Increases Inorganic Carbon in Agricultural Soils

JAMES A. ENTRY*
R. E. SOJKA
USDA Agricultural Research Service
Northwest Irrigation and Soils Research Laboratory
Kimberly, Idaho 83341, USA

GLENN E. SHEWMAKER
University of Idaho
Research and Extension Center
Twin Falls, Idaho 83303-1827, USA

ABSTRACT / Inorganic C reactions are among the most important chemical reactions that occur in irrigated soils and may contribute to the total amount of C sequestered in those soils. Because CO_2 can escape from soils to the atmosphere or return to precipitate carbonate minerals, soils are open systems with regard to inorganic C. We measured inorganic and organic C stored in southern Idaho soils having long-term land-use histories that supported native sagebrush vegetation (NSB), irrigated moldboard plowed crops (IMP), irrigated conservation (chisel) tilled crops (ICT), and irrigated pasture systems (IP). Inorganic C and total C (inorganic + organic C) in soil decreased in the order IMP>ICT>IP>NSB. We use our findings to estimate that amount of possible inorganic and total C sequestration if irrigated agriculture were expanded by 10%. If irrigated agricultural land were expanded by 10% worldwide and NSB were converted to IMP, a possible 1.60 $\times 10^9$ Mg inorganic C (2.78% of the total C emitted in the next 30 years) could be sequestered in soil. If irrigated agricultural land were expanded by 10% worldwide and NSB were converted to ICT, a possible 1.10 $\times 10^9$ Mg inorganic C (1.87% of the total C emitted in the next 30 years) could be sequestered in soil. If irrigated agricultural land were expanded worldwide and NSB were converted to IP, a possible gain of 2.6 $\times 10^8$ Mg inorganic C (0.04% of the total C emitted in the next 30 years) could be sequestered in soils. Inorganic C sequestered from land-use changes have little potential to make a significant impact on the concentration of atmospheric CO_2. However, when coupled with organic C and altering land use to produce crops on high-output irrigated agriculture while selected less productive rain-fed agricultural land was returned to temperate forest or native grassland, there could be reductions in atmospheric CO_2.

In 1992, nearly all countries of the world signed the Framework Convention on Climate Change. The long-term goal of this legislation is to stabilize the concentration of greenhouse gases in the atmosphere at concentrations that prevent interference with the climate system. To stabilize or reduce CO_2 concentrations, emissions of the gas must either be reduced or transferred from the atmosphere to marine or terrestrial ecosystems. Irrigating arid and semiarid regions may be one method to contribute to C sequestration and, ultimately, reduce atmospheric CO_2 concentrations. The addition of water to arid and semiarid soils increases plant growth and, ultimately, C deposition into soil. Entry and others (2002) found that if irrigated agriculture were expanded by 10% into irrigated pastures, a potential increase of 9.3 $\times 10^9$ Mg organic C (16.3% of the total C emitted in the next 30 years) could potentially be sequestered. If irrigated agriculture were expanded 10% and the same amount of rain-fed land were converted back to native forest or grassland, a potential increase of 3.4 $\times 10^9$ or 6.8 $\times 10^9$ Mg organic C (6.0% and 12.9%, respectively, of the total C emitted in the next 30 years) could potentially be sequestered, respectively.

Irrigated agriculture may also sequester small but significant amounts of inorganic C. Inorganic C reactions are among the most important chemical reactions in that occur in irrigated soils and may contribute to the total amount of C sequestered. Calcium content of arid and semiarid region soils is usually elevated compared to temperate regions due to calcium-rich parent material and low rainfall. Carbonate formation is usually controlled by equilibrium reactions in the solid-phase carbonate and gas phase CO_2 (Levy 1980; Robbins 1985; Loeppert and Suarez 1996). Respiratory processes that occur in plant roots and soil microorganisms continually produce CO_2, increasing its concentration in the soil atmosphere and modifying the solubility relationships of carbonate formation and

KEY WORDS: Carbon sequestration; Irrigation; Conservation tillage; Native sagebrush

Published online February 17, 2004.

*Author to whom correspondence should be addressed, *email:* jentry@nwisrl.ars.usda.gov

many plant nutrients. The average $CO_2°$ (Lindsay 1979; Donner and Lynn 1977) in the atmosphere is 0.0003%, whereas the average $CO_2°$ in soils is 0.003%. The average $CO_2°$ in flooded soils ranges from 0.03% to 0.3%. Irrigation water in arid and semiarid regions often contains as much as 1% dissolved CO_2 (Suarez 1977). Increasing the CO_2 dissolved in water increases the rate of carbonate formation (Donner and Lynn 1977).

Because irrigation water flows through a series of canals, where the smaller amounts of water are directly exposed to incoming radiation, irrigation water usually has higher temperatures than stream water or groundwater. Carbon dioxide dissolves in water to form both CO_2^{2-} and HCO_3^- (Lindsay 1979). The solubility of CO_2 in water is highly temperature dependent. Solubility of CO_2 at 0°C is 0.02 mol/L, at 25 C° it is 0.03 mol/L, and at 40°C it is 0.08 mol/L (Donner and Lynn 1977). Therefore, the CO_2 in irrigation water may increase because the temperature of the water may increase from 5°C to 20 C° as water enters the field, but dramatically increase as it comes in contact with the soil surface. Irrigation water flowing through fields having direct exposure to solar radiation on hot days can reach temperatures as high as 40°C. Furrow-irrigation water temperatures may increase as much as 20°C during flow through agricultural fields (Duke 1992). Increased water temperatures will increase reaction time and, under favorable conditions, increase $CaCO_2$ precipitation.

The pH of irrigation water can increase as it flows through irrigation canal systems and agricultural fields by dissolving cations as it comes in contact with basic soils. The fraction of the dominant carbonate ion in solution at pH 4–6 is a nonreactive H_2CO_3, at pH 7–9 the dominant ion is a more reactive HCO_3^-, and at pH 10–12 the dominant ion is a very reactive CO_2^{2-}. The activity of the dissolved HCO_3^{2-} ion increases 10-fold for each unit increase in pH, whereas the activity of the dissolved CO_2^{2-} ion increases 100-fold for each unit increase (Lindsay 1979). Irrigated soils are typically in regions of low rainfall and thus usually have high a pH value, which can favor inorganic C formation. Irrigated arid or semiarid soils can be conducive to inorganic C precipitation compared to native sites due to high pH resulting from high Ca concentration and increased CO_2 in the soil atmosphere as a result of increased plant growth, increased microbial activity, and higher soil moisture from irrigation events.

Therefore, when irrigation water having high concentrations of Ca and dissolved HCO_3^- and CO_2^{2-} ions combined with a high pH and an elevated temperature is applied to soil, $CaCO_3$ can, and often does, precipitate. The objective of this research was to determine if land managed as irrigated moldboard plowed crops, irrigated conservation tillage, or irrigated pasture would increase the amount of inorganic C in soil compared to native sagebrush vegetation. We use our findings to determine the influence of inorganic C on total C (organic + inorganic C) of altered land management polices that could favor global C sequestration based on the C budgets that we have estimated.

Materials and Methods

Site Descriptions

The study area is located on the Snake River Plain, between 42°30′00″ and 43°30′00″ N. and 114°20′00″ and 116°30′00″ W. The area is classified as a temperate semidesert ecosystem (Bailey 1998). The climate is typified by cool, moist winters and hot, dry summers, with annual precipitation ranging from 175 to 305 mm, two-thirds of which occurs during October through March (Collett 1982). Vegetation throughout the general area was historically dominated by basin big sagebrush (*Artemisia tridentata* var. *tridentata* Nutt.) and perennial bunch grasses. Vegetation and soils are more thoroughly described in Entry and others (2002).

Experimental Design

The experiment was arranged in a completely randomized design (Kirk 1982). Soil samples were taken from (1) three sites supporting native sagebrush vegetation (NSB) located near agricultural land in southern Idaho (each site supported a basin big sage and a Wyoming big sage vegetation type), (2) three sites that were formerly crop land and converted to and maintained as irrigated pasture (IP) for the past 30 years, (3) three sites that were irrigated crop land and have been managed with conservation tillage (ICT) for the past 8 years, and (4) three irrigated agricultural crop lands in moldboard plowing systems (IMP). There were 4 treatments (NSB, IMP, ICT, and IP) times 3 sites for each treatment times 3 cores taken within each treatment at each site (replications) times 4 soil depths (0–5 cm, 5–15 cm, 15–30 cm, and 30–100 cm), for a total of 144 samples.

Vegetation

Native sagebrush sites were vegetated with native steppe vegetation. Sites were chosen for this study based on a history of no livestock grazing (BLM, Bruneau Resource Area, unpublished data). All study sites had a 5–10% slope and supported basin big sagebrush or Wyoming big sagebrush or community types. Soil classifications are described in Entry and others (2002).

Three irrigated pastures were selected that were formerly crop land and converted to and maintained as IP for the past 30 years. The Buhl site was vegetated with Kentucky bluegrass (*Poa pratensis* L.)–orchardgrass (*Dactylis glomerata L.*) on a Xerollic Durargids soil. The Gooding site was vegetated with smooth brome (*Bromus inermis* Leyss.)– orchardgrass on Xerollic Haplargid soil. The Kimberly site was vegetated with smooth brome– orchardgrass pasture on a Xeric Haplocalcid soil. Grazing rates on these pastures were 10–12 animal unit months/year

Three sites with fields rotating among alfalfa (*Medicago sativa* L.), wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), and beans (*Phaseolus vulgaris* L.) that were managed with moldboard plowing were sampled. All sites were located on fields managed by USDA Agricultural Research Service's Northwest Irrigation and Soils Research Laboratory or the University of Idaho, Research and Extension Center. Soil on all sites was classified as a coarse- silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid, with 0.1–0.21 g/g clay and 0.6–0.75 g/g silt, organic matter of ~13 g/kg, and soil pH of 7.6–8.0. The slopes on these sites ranged from 1.0% to 3.0%.

Three sites with fields rotating among alfalfa, wheat, potato, and beans that had been managed with conservation (chisel) tillage were sampled. Soil on all sites was classified as a coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid, with 0.1–0.21 g/g clay and 0.6–0.75 g/g silt and organic matter of ~13 g/kg. The soil has a pH of 7.6–8.0. The slopes on these sites range from 1.0% to 3.0%.

Sampling Procedures

We sampled the top 1 m of soil each season (winter, spring, summer, and autumn) to determine if the amount of C in soil would be affected by irrigation, tillage, and vegetation. Sampling locations were randomly chosen at each site or field. Three separate 2.4-cm-diameter replicate cores were randomly taken at each season and partitioned into 0–5-cm, 5–15-cm, 15–30-cm, and 30– 100-cm depths. Roots greater than 1.0 cm in diameter were measured separately.

Soil Carbon

The concentration of inorganic C in each sample of mineral soil was determined by the titration procedure described in Loeppert and Suarez (1996). The concentration of organic C in each sample of mineral soil was determined by the Walkley–Black procedure (Nelson and Sommers 1996). The amount of C per hectare of the 0–100 cm of mineral soil was calculated assuming 0.44 g C/g organic matter with correction for soil bulk density. Ten separate 10-cm-diameter soil cores were taken to a 1.0-m depth, divided into 0–5-cm, 5–15-cm, 15–30-cm, and 30–100-cm depths to determine bulk density. Bulk density was measured by dividing the oven dry weight after drying at 105°C for 48 h by the volume of the sample (Blake and Hartage 1982).

When assessing the potential of irrigation of arid or semiarid land to increase C storage in soils, one needs to assess C loss from CO_2 emitted to the atmosphere as a result of (1) fertilizer manufacture, storage, transport, and application, (2) fossil fuel CO_2 emitted from pumping irrigation water, (3) farm operations, such as tillage and planting, and (4) CO_2 lost via dissolved carbonate in irrigation water (Schlesinger 1999; West and Marland 2001). Schlesinger (1999) used a fertilization value of 336 kg N/ha/year, which is an unusually high fertilization rate in US farms. The CO_2 released during fertilizer production of 336 kg N/ha/year is ~16.7 g C/m^2/year (Schlesinger 1999). It has been noted that a more realistic rate is 100–150 kg N/ha/year (West and Marland 2001). Carbon dioxide released from pumping irrigation water in the United States ranges from 126 kg C/ha/year when using gasoline to 266 kg C/ha/year when using electricity (West and Marland 2001). In addition, C may be lost as CO_2 from the irrigation water itself. Irrigation water in arid and semiarid regions often contains as much as 1% dissolved CO_2. When water is applied to the soil, $CaCO_3$ can precipitate, releasing CO_2 into the atmosphere. If irrigation water containing 0.05 g/L dissolved Ca is used to irrigate crops in semiarid climates, the calculated increase in plant C is 2000 g C/m/year over C contained in native soils and vegetation. The net CO_2 released via irrigation water is calculated to be 8.4 g C/m/year (Schlesinger 1999).

Calculations

Concentrations of inorganic and organic C were converted, using bulk density measurements, to a meter square basis to a depth of 1 m. Inorganic and total C (in kg/m) was converted to megagrams of C per hectare by multiplying by 10,000 (land area) and dividing by 1,000 (C weight), which is a 1:10 conversion. Using the values obtained in southern Idaho, we estimated C storage in soils locally and regionally if all land presently managed as IMP in the Pacific Northwestern United States (PNW) and western United States was converted to ICT and if 10% of land managed as IMP in the PNW and western United States was converted to IP. Because increased agricultural production will be necessary to feed an increasing population, it is impractical to suggest that a large portion of land in IMP can be converted to IP. We divided the resulting number by 10 to

Table 1. Inorganic and organic C in soils, aboveground biomass, and on sites at present, C emitted during agricultural operations, and net total C in soil and on site.

Vegetation	Carbon present in soil ($kg C/m^2$)			Carbon present ($kg C/m^2$)		Carbon emitted ($kg C/m^2$)	Net carbon ($kg C/m^2$)	
	Organic	Inorganic	Total	Aboveground	Site		Soil	Site
Native sagebrush	5.91c	9.50c	15.41c	0.42a	15.83c	0.00d	15.41c	15.83c
Irrigated moldboard plow crop	7.29b	15.60a	22.89a	0.00c	22.89a	1.10a	21.79a	21.79a
Irrigated conservation tilled crops	8.01b	13.60a	21.61a	0.00c	21.61a	0.87b	20.74a	20.74a
Irrigated pasture	10.14a	8.50b	18.64b	0.05b	18.69b	0.29c	18.35b	18.40b

Notes: In each column, values followed by the same letter are not significantly different as determined by the least square means test ($P \leq 0.05$; $n = 16$).
Values of organic C are determined by the Walkley–Black procedure.
Values of inorganic C are determined by titration.
Carbon in soils, aboveground vegetation and on the site at the present time.
Estimated C emitted in production of fertilizer, fuel consumption in farm operations over a 30-year period.

account for a 10% conversion of one treatment (land area). The amount of C sequestered in the PNW States and the 11 western states in the United States was estimated by multiplying megagrams of C per hectare by the number of hectares of irrigated land in each area. There are 9,055,979 ha of land in irrigated crop land in the PNW and 24,322,029 ha in the western United States. (Bucks and others 1990; Tribe 1994; Howell 2000). Inorganic and total C sequestered (C_S) relative to the amount of C projected to be emitted worldwide during the next 30 years (C_{EW}) was calculated by dividing the megagrams of C sequestered in each treatment × the area by the total projected worldwide release of CO_2–C during the next 30 years (5.7×10^{10} Mg C) and then multiplying by 100 to convert to a percent basis.

Statistical Analysis

All data were subjected to a one-way vegetation-type analysis of variance (ANOVA) for a completely randomized design (Snedecor and Cochran 1980; Kirk 1982). Residuals were normally distributed with constant variance. SAS software programs (SAS Institute Inc. 1996) were used to conduct the ANOVA. Significance of treatment means were determined at $P < 0.05$ with the least square means test.

Results

Site-Specific Findings

Initial organic C in soils was greater in the IP treatment than the other vegetation types (Table 1). Inorganic and total (organic + inorganic) C was higher in soils supporting IMP, ICT, and IP vegetation than soils with NSB vegetation. Organic C contained in aboveground vegetation was greater on NSB sites than IP; however, IP biomass was removed by grazing. Crops were not considered as permanent vegetation and thus assigned a value of zero. After adjustment for agricultural CO_2 emissions, (net) C in soils was greater in the IMP and least in the NSB vegetation. Net inorganic and total C on the soils decreased in the order IMP>ICT>IP>NSB (Table 1).

Implications of Expanding Irrigated Agriculture

Inorganic carbon sequestration. Data from our samples were used to calculate potential inorganic C storage for irrigated agriculture in the PNW U.S. and western United States over a 30-year period. If irrigated agricultural land size is expanded by 10%, meaning NSB land is converted to IMP, ICT, or IP, we estimated a gain of 6.1, 4.1, and 1.0 Mg inorganic C/ha, respectively (Table 2). Using these values to represent inorganic C gain or loss for all irrigated crop land in the PNW, if irrigated agricultural lands were expanded by 10% and NSB were converted to IMP, a possible 5.5×10^7 Mg inorganic C (0.1% of the total C emitted in the next 30 years) could be sequestered in irrigated agricultural soils. If irrigated agricultural lands were expanded by 10% and NSB were converted to ICT, a possible 3.7×10^7 Mg inorganic C (0.07% of the total C emitted in the next 30 years) could be sequestered in irrigated agricultural soils. If irrigated agricultural land were expanded by 10% and NSB were converted to IP, a possible gain of 9.0×10^6 Mg inorganic C (0.02% of the total C emitted in the next 30 year) could be sequestered in soil.

Using these values to represent inorganic C gain or loss for all irrigated crop land in the western United States, if irrigated agricultural land were expanded by

Table 2. Inorganic C sequestered in soils by a 10% expansion of arid or semiarid land to irrigated lands agriculture.

Vegetation conversion	C gained from a 10% conversion	Pacific Northwest United States (Mg C/ha)	Pacific Northwest United States Mg C	Western United States % $C_SC^a_{EW}$	Western United States Mg C	Worldwide %C_SC_{EW}	Worldwide Mg C
Native sagebrush to irrigated moldboard plow	6.1	5.5×10^8	0.97	1.5×10^9	2.60	1.6×10^9	2.78
Native sagebrush to irrigated conservation tillage	4.1	3.7×10^7	0.07	1.0×10^9	0.17	1.1×10^9	1.87
Native sagebrush to irrigated pasture	1.0	9.0×10^6	0.02	2.4×10^7	0.04	2.6×10^8	0.04

Note: Land area in irrigated crop land is 9,055,979 ha; in the Pacific Northwest 24,322,029 ha in the Western United States, and 260,000,000 ha worldwide.

[a]% C_SC_{EW} = C sequestered (C_S) divided by the amount of C projected to be emitted worldwide during the next 30 years, which is 5.7×10^{10} Mg C (C_{EW} multiplied by 100.

Table 3. Total (organic and inorganic) C sequestered in soils by a 10% expansion of arid or semiarid land to irrigated lands agriculture

Vegetation conversion	C gained from a 10% conversion	Pacific Northwest United States (MgC/ha)	Pacific Northwest United States Mg C	Western United States % C_S/C^a_{EW}	Western United States Mg C	Worldwide % C_S/C_{EW}	Worldwide Mg C
Native sagebrush to irrigated moldboard plow	6.1	5.3×10^7	0.10	1.5×10^8	0.25	1.9×10^9	2.72
Native sagebrush to irrigated conservation tillage	4.9	4.4×10^7	0.04	1.2×10^8	0.20	1.3×10^9	1.17
Native sagebrush to irrigated pasture	2.6	2.3×10^7	0.04	6.3×10^7	0.10	1.7×10^8	1.17

Note. Land area in irrigated crop land is 9,055,979 ha, in the Pacific Northwest 24,322,029 ha, in the Western United States and 260,000,000 ha worldwide.

[a]% C_S/C_{EW} = C sequestered (C_S) divided by the amount of C projected to be emitted worldwide during the next 30 years, which is 5.7×10^{10} Mg C (C_{EW}) multiplied by 100.

10% and NSB were converted to IMP, a possible 1.0×10^9 Mg inorganic C (0.17% of the total C emitted in the next 30 year) could be sequestered in soil (Table 2). If irrigated agricultural land were expanded by 10% and NSB were converted to ICT, a possible 1.0×10^9 Mg inorganic C (0.17% of the total C emitted in the next 30 years) could be sequestered in soil. If irrigated agricultural land were expanded and NSB were converted to IP, a possible gain of 2.4×10^7 Mg inorganic C (0.04 % of the total C emitted in the next 30 years) could be sequestered in soils.

Using these values to represent inorganic C gain or loss for all irrigated crop land in the worldwide, if irrigated agricultural land were expanded by 10% and NSB were converted to IMP, a possible 1.60×10^9 Mg inorganic C (2.78% of the total C emitted in the next 30 year) could be sequestered in soil (Table 2). If irrigated agricultural land were expanded by 10% and NSB were converted to ICT, a possible 1.10×10^9 Mg inorganic C (1.87% of the total C emitted in the next 30 years) could be sequestered in soil. If irrigated agricultural land were expanded and NSB were converted to IP, a possible gain of 2.6×10^8 Mg inorganic C (0.04% of the total C emitted in the next 30 years) could be sequestered in soils.

Total carbon sequestration. These data were used to calculate potential total C storage for irrigated agriculture in the PNW and western United States over a 30-year period. If 10% of the NSB land is brought under cultivation to IMP, ICT, or IP, we estimated a gain of 6.0, 4.9, and 2.6 Mg C/ha, respectively (Table 3). Using these values to represent C gains for all irrigated crop land in the PNW, if irrigated agricultural land were expanded by 10% and NSB were converted to IMP, a possible 5.3×10^7 Mg C (0.10% of the total C emitted in the next 30 years) could be sequestered in soil. If land irrigated agriculture were expanded by 10% and NSB were converted to ICT, a possible 4.4×10^7 Mg C (0.08% of the total C emitted in the next 30 years) could be sequestered in soil. If land irrigated

Table 4. Potential C transfer by converting 10% of land currently in rain-fed moldboard plow land to native forest and native grass land on a 1-unit to 1-unit basis and conversion of 10% of rain-fed moldboard plow land to native forest and native grassland on a 2-unit to 1-unit basis

10% Conversion of vegetation from rain-fed land in moldboard plow	(Mg C/ha)	Pacific Northwest United States		Western United States		Worldwide	
		Mg C	% C_S/C_{EW}^a	Mg C	% C_S/C_{EW}	Mg C	% C_S/C_{EW}
Rain-fed moldboard plow to native forest on a 1-unit to 1-unit basis	0.56	5.1×10^6	0.01	1.4×10^7	0.02	1.5×10^8	0.23
Rainfed moldboard plow to native grassland on a 1-unit to 1-unit basis	1.30	1.0×10^7	0.02	2.8×10^7	0.05	3.4×10^8	0.59
Rain-fed moldboard plow to native forest on a 2-unit to 1-unit basis	1.12	1.4×10^7	0.03	3.9×10^7	0.07	2.91×10^8	0.51
Rain-fed moldboard plow to native grassland on a 2-unit to 1-unit basis	2.60	2.8×10^7	0.05	7.4×10^7	0.13	6.7×10^8	1.19

*Note:*Irrigated agricultural land typically produces twice the yield as rainfed agriculture.

[a]% C_S/C_{EW} = C sequestered (C_S) divided by the amount of C projected to be emitted worldwide during the next 30 years, which is 5.7×10^{10} Mg C (C_{EW}) multiplied by 100.

agriculture were expanded by 10% and NSB were converted to IP, a possible 3.4×10^8 Mg C (0.60% of the total C emitted in the next 30 years) could be sequestered in soil.

Using these values to represent C gains for all irrigated crop land in the western United States, if land irrigated agriculture were expanded by 10% and NSB were converted to IMP, a possible 1.5×10^7 Mg C (0.25% of the total C emitted in the next 30 years) could be sequestered in irrigated agricultural soils. If land irrigated agriculture were expanded by 10% and NSB were converted to ICT, a possible 13×10^7 Mg C (0.02% of the total C emitted in the next 30 years) could be sequestered. If land irrigated agriculture were expanded by 10% and NSB were converted to IP, a possible 6.3×10^7 Mg C (0.10% of the total C emitted in the next 30 years) could be sequestered.

Using these values to represent C gains for all irrigated crop land worldwide, if land irrigated agriculture were expanded by 10% and NSB were converted to IMP, a possible 1.6×10^9 Mg C (2.72% of the total C emitted in the next 30 years) could be sequestered in irrigated agricultural soils. If land irrigated agriculture were expanded by 10% and NSB were converted to ICT, a possible 1.3×10^9 Mg C (2.24% of the total C emitted in the next 30 years) could be sequestered. If land irrigated agriculture were expanded by 10% and NSB were converted to IP, a possible 1.7×10^8 Mg C (1.17% of the total C emitted in the next 30 years) could be sequestered.

Conversion of rain-fed land to native vegetation. If crops were produced via high-output irrigated agriculture while less productive rain-fed agricultural land were returned to temperate forest or native grassland, an increase of 5.6 and 13.0 Mg C/ha, respectively, could be gained over 30 years for each unit of rain-fed land converted to native vegetation (Table 4). Using a conversion basis of 1 unit of irrigated agriculture to return 1 unit of rain-fed agricultural land to native forest, if irrigated agriculture were expanded 10% (meaning that an additional 2.6×10^7 ha of arid or semiarid land were irrigated) and the equal amount of land being managed as rain-fed agricultural land were converted to native forest, there is potential to sequester 5.1×10^6 Mg C (0.01% of the total C emitted in the next 30 years) in the PNW, 1.4×10^7 Mg C (0.02% of the total C emitted in the next 30 years) in the western United States and 1.5×10^8 Mg C (0.23% of the total C emitted in the next 30 years) worldwide. If the rain-fed agricultural land were converted to native grassland, there is a potential to sequester 1.0×10^7 Mg C (0.02% of the total C emitted in the next 30 years) in the PNW, 2.8×10^7 Mg C (0.05% of the total C emitted in the next 30 years) in the western United States, and 3.4×10^8 Mg C (0.59% of the total C emitted in the next 30 years) worldwide.

However, irrigated agricultural land typically produces twice the crop yield of rain-fed agricultural land (Bucks and others 1990; Howell 2000). If irrigated agriculture were expanded 10%, each hectare of new irrigated land could produce the same crop yield as 2 ha of rain-fed land (Bucks and others 1990; Tribe 1994; Howell 2000). Under this scenario, if irrigated agricultural land was expanded and an equal amount of rainfed agricultural land were returned to native forest, we could potentially sequester 1.4×10^7 Mg C (0.03% of the total C emitted in the next 30 years) in the PNW, 3.9×10^7 Mg C (0.68% of the total C emitted in the next 30 years) in the western United States, and 2.9×10^8 Mg C (0.51% of the total C emitted in the next 30 years) in the western United States (Table 4). If irrigated agricultural land was expanded and an equal amount of rain-fed agricultural land were returned to native grassland in this 2 : 1 conversion scenario, there is a potential to sequester 2.8×10^7 Mg C (0.05% of the total C emitted in the next 30 years) in the PNW 7.4×10^7 Mg C (0.13% of the total C emitted in the next 30 years) in the western United States, and 6.7×10^8 Mg C (1.19% of the total C emitted in the next 30 years) worldwide.

Discussion

Soils in arid or semiarid lands there may contain substantially more inorganic than organic C. Inorganic C is present because there is insufficient precipitation to leach basic cations from the soil. Some of the basic cations form carbonates with CO_3^- sequestering C. When arid or semiarid lands are initially converted to agriculture, basic cations may be leached from soil and CO_2 may be emitted to the atmosphere by dissolution of carbonate minerals. If irrigation water contains a high concentration of basic cations, C may be sequestered by the reactions of elevated concentrations of CO_2 in the soil atmosphere with Ca or Mg dissolved in the water.

Our results indicate that there is a greater amount of inorganic C sequestered in IMP than NSB or IP soils. It may be that IMP without vegetative or organic matter debris soils are exposed to more direct solar radiation and thus higher temperatures during hot summer irrigation periods that ICT or IP soils. Greater soil organic matter concentration in soil may also lead to organic acid synthesis that may dissolve carbonates or inhibit carbonate formation. The effect may be more important in arid irrigated areas with high HCO_3 and CO_3 concentrations compared to rain-fed areas. Inorganic C sequestration in the future may be less significant because many producers are converting from furrow to sprinkler irrigation, which typically requires less water. Irrigation farmers are converting to sprinkler systems because (1) after the initial cost of investment, it is more economical than furrow irrigation, (2) sprinkler systems are easier to manage and provide more accurate water management than furrow irrigation, (3) sprinkler systems produce decreased erosion and ultimately reduce loss of fertilizer nutrients, (4) sprinkler irrigation provides increased irrigation control, leading to less weed seed and plant pathogens in return water applied to downstream fields, and (5) decreased runoff and leaching and thus input of nutrients and agricultural chemicals to return flow and ultimately surface and groundwater. Surface irrigation requires far more water application to crops than sprinklers. Surface irrigation is inefficient because of large deep percolation and runoff losses that rely on soil and gravity to transport and distribute water. In the Jiftlik Valley of Jordan, switching from surface to sprinkler and drip irrigation resulted in increasing the irrigated area 10-fold while using the same amount of water (Keen 1991). Use of sprinkler and drip irrigation allowed more intensive cropping, resulting in greater labor use, loans to implement the technology being repaid in 3–4 years, average agricultural income increasing 13–15-fold, and commercial off farm benefits increasing eightfold (Keen 1991). In the western United States, conversion from surface to sprinkler irrigation on well-managed fields typically saves 30–40% of water applied to the field (Trout and others 1994). However, in most countries, some form of surface irrigation is used mainly because money to acquire sprinkler or subsurface irrigation technology is unavailable, because skills of using the new systems is unavailable, and due to institutional desire to use manual labor to support and maintain agricultural populations (Unger and Howell 1999). Water saved through conversion to sprinkler systems may reduce the amount of inorganic C sequestered, but it will also allow 30–40% more land to be irrigated, resulting in increased organic C sequestration.

The conversion to sprinkler or drip irrigation may reduce the amount of inorganic C in IMP soils due to less total irrigation water applied. Conversion of all IMP land to ICT or 10% of IMP land to IP lands is insignificant compared to the amount of C projected to be emitted in the next 30 years. It is only when irrigated agriculture is expanded and/or rain-fed agricultural land is converted back into native forest or grasslands that substantial gains are projected. In most cases, converting selected land managed as IMP to ICT or IP can be implemented with modest economic impact to landowners and poses relatively few socioeconomic issues. Conversion of surface to sprinkler irrigation improves water-use efficiency and reduces C transport off site via sediment and water because of dramatic reductions of offsite flow and leaching (Aase and others 1998). The use of conservation tillage and improved sprinkler irrigation systems to reduce erosion, especially in combination with new technologies such as the use of polyacrylamide to reduce topsoil erosion, and thus loss of C from fields, have the potential to further reduce C transport and degradation. Additional C that may be sequestered resulting from improved long- term inputs of technology needs to be determined to more accurately predict potential C gains by irrigated agriculture in the future. Our estimates made no attempt to adjust C budgets for loss of C due to erosion. Because great improvements in controlling irrigation-induced erosion have occurred in recent years, it is likely that our C storage estimates for irrigated agriculture are conservative. If agricultural land is managed properly, these practice shifts would also potentially reduce erosion and water or air pollution.

Because nearly one-third of the yield and nearly one-half of the value of crops in the United States are produced on irrigated lands predominantly in arid or semiarid climatic zones (Bucks and others 1990; Tribe 1994; Howell 2000), a strong strategic rationale can be made for expanding irrigated agriculture in these areas for both crop production and C sequestration if accompanied by selective return of rainfed agricultural land derived from forest, grassland, or wetlands back to native vegetation. The potential C sequestered on site by conversion of native vegetation to irrigated agriculture is above the steady-state equilibrium of native vegetation. This is in contrast to rain-fed agricultural systems currently attempting modest C gains to attain near- baseline C concentrations by implementing reduced or no-tillage practices. Rain-fed agricultural lands with or without no-till practices have soil C values far below those of forest or grassland vegetation.

Policy-makers and agricultural research infrastructure should recognize the enormous potential benefit of land and water management strategies, polices and incentives that could expand arid zone irrigated agriculture as a means for efficient food and fiber production along with substantial C sequestration potential. This potential would be enhanced if coupled with selective return of less efficient rain-fed agricultural lands derived from forest, grassland, or wetlands back to native vegetation. We recognize that such an expansion would have to be accompanied by renewed efforts of water development. Water resource development has been occurring at a modest pace worldwide since 1990. Howell (2000) indicated the potential for increased extent of irrigation via efficiency improvements and wastewater use. Recognition of these potential C benefits should provide an incentive to fund research and pursue management strategies that are possible without sacrificing production and which could increase restoration of native ecosystems, reduce erosion, and improve water quality through appropriate targeting of the strategy.

We recognize that the values for potential C gain in our study are estimates. To obtain a more precise value of potential C sequestration from management conversions on a regional basis, it would be necessary to investigate the potential C accumulated in many different soils supporting many different vegetation types. Use of these data from Idaho provides an indication of the potential for these kinds of management shift on a larger scale. Our estimated values for C may actually be conservative due to improving land management methods and improving irrigation technology. The C trends that we monitored were the end result of management that predated new technology now available that would have prevented much of the erosion and loss of soil C on our monitored irrigation sites. Most irrigated agriculture worldwide uses surface irrigation, with substantial runoff resulting in some transport off site of C via erosion with sediment and dissolved C in the water.

Literature Cited

Aase, J. K., D. L. Bjorneberg, and R. E. Sojka. 1998. Sprinkler irrigation runoff and erosion control with polyacrylamide - laboratory tests. *Soil Science Society of America Journal* 2:1681–1687.

Bailey, R. G. 1998. Ecoregions of North America. US Department of Agriculture. Forest Service, US Government Printing Office, Washington, DC.

Blake, G. R., and K. H. Hartage. 1982. Bulk density. Pages 363–375 *in*. Page . *in* A. L. Page, R. H. Miller, and D. R. Keeney. (eds.), Methods of soil analysis. Part 2. Chemical and microbiological properties. American Society of Agronomy, Madison, Wisconsin.

Bucks, D. A., T. W. Sammis, and G. L. Dickey. 1990. Irrigation for arid areas. Pages 449–548 *in*. Page . *in* G. J. Hoffman, T. A. Howell, and K. H. Solomon. (eds.), Management of farm irrigation Systems. American Society Agricultural Engineers. St. Joseph, Missouri.

Collett, R. A. 1982. Soil Survey of Ada County area. US Department of Agriculture, Natural Resources Conservation Service., US Government Printing Office, Washington, DC, 182 pp.

Donner, H.E., and W.C. Lynn. 1977. Carbonate, Halide, Sulfate and Sulfide Minerals. Pages 75– 96 *in*. Page . *in* R. C. Dinauer, J. Nagler, and J. H. Nauseef. (eds.), Minerals in the soil environment. American Society of Agronomy, Madison, Wisconsin.

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

Entry, J. A., R. E. Sojka, and G. Shewmaker. 2002. Management of irrigated agriculture to increase carbon storage in soils. *Soil Science Society of America Journal* 66:1957–1964.

Howell, T. A. 2000. Irrigations role in enhancing water use efficiency. Pages 67–80 *in*. Page . *in* R. G. Evans, B. L. Benham, and T. P. Trooien. (eds.), National irrigation symposium. American Society of Engineers, St. Joseph, Missouri.

Keen, M. 1991. Drip-trickle irrigation boosts Bedouin farmers yields. *Cereal Research 130* 24:10–12.

Kirk, R. E. 1982. Experimental design: Procedures for the behavioral sciences. 2nd ed. Brooks/Cole Publishing, Monterey, California, 911 pp.

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.

Lindsay, W. L. 1979. Chemical equilibria in soils. John Wiley & Sons, New York, 449 pp.

Loeppert, R. H., and Suarez, D. L. 1996. Carbonate and gypsum. Pages 437–474 *in* D. L., Sparks, A.L. Page, P.A. Halmke, R.H. Loeppert, P.N. Solterpour, M.A. Tabatabui, C.T. Johnson, and M.E. Sumner (eds.). Methods of soil analysis. Part 3, Chemical Methods D. L. American Society of Agronomy, Madison, Wisconsin.

Nelson, D. W., and L. E. Sommers. 1996. Total carbon, organic carbon and organic matter. Pages 961–1010 *in. in* J. M. Bigham (ed.), Methods of soil analysis. Part 3. Chemical and microbiological properties. American Society of Agronomy, Madison, Wisconsin.

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

SAS Institute Inc 1996. SAS user's guide: statistics – Version 6.03 edition. Statistical Analysis System (SAS) Institute Inc, Cary, North Carolina, 584 pp.

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

Snedecor, W. G., and W. G. Cochran. 1980. Statistical methods. 7th ed. Iowa State University Press, Ames, Iowa, 354 pp.

Suarez, D. L. 1977. Ion activity products of calicum carbonate in waters below the root zone. *Soil Science Society of America Journal* 41:310–315.

Tribe, D. 1994. Feeding and greening the world: The role of agricultural research. CAB International, Wallingford, United Kingdom, 274pp.

Trout, T. J., D. C. Kincaid, and D. T. Westermann. 1994. Comparison of russet Burbank yield and quality under furrow and sprinkler irrigation. *American Potato Journal* 71:15–28.

Unger, P. W., and T. A. Howell. 1999. Agricultural water conservation — A global perspective. Pages 1–36 *in.* Page . *in* M. B. Kirkham (ed.), Water use and crop production. Food Products Press, Binghamton, New York.

West, T. O., and G. Marland. 2001. 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.