

Irrigation Increases Carbon in Agricultural Soils

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Abstract. Irrigated agriculture sequesters significant amounts of organic C. Irrigation may also sequester significant amounts of inorganic C. Inorganic C reactions are important chemical reactions in irrigated soils and may contribute to the total amount of C sequestered. Calcium content of arid and semi-arid soils tends to be higher than rainfed temperate soils due to calcium rich parent material and low rainfall. Carbonate formation is usually controlled by carbonate equilibrium reactions in the solid and gas phase CO_2. Respiration in plant roots and soil microorganisms continually produce CO_2 increasing its concentration in the soil atmosphere, modifying carbonate solubility. Since irrigation water flows through a series of canals, where smaller amounts of water are directly exposed to incoming radiation, irrigation water usually has higher temperatures than stream or ground water. Carbon dioxide dissolves in water to form both CO_2 as a gas and H_2CO_3 in solution. Warmer water increases reaction time and, in favourable conditions, precipitates $CaCO_3$ .We measured organic and inorganic C stored in southern Idaho soils having long term land use histories that supported native sagebrush vegetation (NSB), irrigated mouldboard ploughed 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 the amount of possible organic, 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 1.90×10^9 Mg total (organic +inorganic) C (2.72 % of the total C emitted in the next 30 yr) could be sequestered in soil. If irrigated agricultural lands were expanded by 10% worldwide and NSB were converted to ICT, a possible 1.30×10^9 Mg total C (2.24 % of the total C emitted in the next 30 yr) could be sequestered in soil. If irrigated agricultural land were expanded worldwide and NSB were converted to IP a possible gain of 1.7×10^8 Mg total C (1.174 % of the total C emitted in the next 30 yr) could be sequestered in soils. Altering land use to produce crops on high output irrigated agriculture, while selected less-productive rainfed agricultural land were returned to temperate forest or native grassland, there could be meaningful reductions in atmospheric CO_2.

INTRODUCTION

The pH of irrigation water can increase as it flows through canal systems and from reuse through agricultural fields by dissolving cations as it comes in contact with basic soils. The activity of H_2CO_3 increases 10 fold per unit increase in pH, whereas CO_2 activity increases 100 fold per pH unit increase (Lindsay, 1979). When irrigation water having high concentrations of Ca and dissolved H_2CO_3 and CO_2°, a high pH value, and an elevated temperature is applied to soil, $CaCO_3$ often precipitates. This research sought to determine if land managed as irrigated mouldboard ploughed crops, irrigated conservation tillage, or irrigated pasture increases soil inorganic C compared to native sagebrush vegetation. We use our findings to consider potential land management polices that could favour global C sequestration based on our estimated C budgets.

MATERIALS AND METHODS

Experimental design

The experiment was arranged in a completely randomised design. 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 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 mouldboard ploughing systems (IMP). There were four treatments (NSB, IMP, ICT, and IP) x 3 sites for each treatment x 3 cores taken within each treatment at each site (replications) x 4 soil depths (0-5 cm, 5-15 cm, 15-30 and 30-100 cm), for a total of 144 samples.

Vegetation

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 and is classified as a temperate semi-desert ecosystem (Bailey, 1998). The climate has cool, moist winters and hot, dry summers with annual precipitation ranging from 175 to 305 mm, two-thirds occurring during October through March (Bailey, 1998). Native vegetation (NSB sites) was historically dominated by basin big sagebrush (*Artemisia tridentata* var. *tridentata* Nutt.) and perennial bunch grasses. Three irrigated pastures were selected that were formerly crop land and converted to and maintained as irrigated pasture (IP sites) for the past 30 years. Grazing rates on these pastures were 10-12 animal unit months yr^{-1}. Three sites with mouldboard ploughed fields (IMP sites) rotating among alfalfa (*Medicago sativa* L.), wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.) and beans (*Phaseolus vulgaris* L.) were sampled. Three sites were conservation (chisel) tillage fields (ICT sites) rotating among alfalfa, wheat, potato and beans.

Sampling and carbon analysis

Three 10 cm diameter replicate cores were randomly taken and partitioned into the above stated soil depths. Concentration of inorganic C in each sample of mineral soil was determined by the titration procedure of Loeppert and Suarez (1996). 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 ha^{-1} of the 0-100 cm of mineral soil was calculated assuming 0.44 g C g^{-1} organic matter correcting for soil bulk density. We estimated C loss as CO_2 emitted to the atmosphere due to 1) fertiliser manufacture, storage, transport and application, 2) fossil- fuel CO_2 from pumping irrigation water, 3) farm operations, such as tillage and planting, and 4) CO_2 lost via dissolved carbonate in irrigation water (West and Marland, 2001). Using the southern Idaho values, we estimated C storage in soils locally and regionally if all land presently managed as IMP in the Pacific Northwestern (PNW) and western U.S. was converted to ICT and if 10 % of land managed as IMP in the PNW and western U.S. was converted to IP.

RESULTS

Organic C in soils was greatest in the IP treatment (Table 1). Soil inorganic and total (organic + inorganic) C was higher IMP, ICT and IP treatments than NSB soils. Organic C in above-ground vegetation was greater on NSB sites than IP; however, IP biomass was removed by grazing. Crops not being permanent vegetation and thus were assigned a value of 0. Conversion of NSB land to IMP sequestered more inorganic and total C than ICT (Table 1). 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. Inorganic and organic C in soils, aboveground biomass and on sites at present, C emitted during agricultural operations, net total C in soil and on site

Vegetation	Carbon present in soil			Carbon present		Carbon	Net carbon	
	Organic	Inorganic	Total	Aboveground Kg C m^2	Site	Emitted	Soil	Site
Native sagebrush	5.91c	9.50c	15.41c	0.42a	15.83c	0.00d	15.41c	15.83c
Irrigated mould-board plough crop	7.29b	15.60a	22.89a	0.00c	22.89a	1.10a	2.179a	21.79a
Irrigated conser-vation 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

[a]In each column, values followed by the same letter are not significantly different as determined by the least square means test (p # 0.05; n = 16).
[b]All data were subjected to a one-way analysis of variance for a completely randomised design. Residuals were normally distributed with constant variance. Significance of treatment means were determined at $P < 0.05$ with the last squares means test.

Table 2. Total (organic and inorganic) C sequestered in soils by a 10% expansion of arid or semi-arid land to irrigated lands agriculture

Vegetation Conversion	C gained from a 10% conversion	Pacific Northwest United States		Western United States		Worldwide	
	Mg C ha	Mg C ha	C_s/C_{EW}	Mg C ha	C_s/C_{EW}	Mg C ha	C_s/C_{EW}
Native sagebrush to irrigated conservation tillage	4.9	4.4 x 10^7	0.08	1.2 x 10^7	0.20	1.3 x 10^9	2.24
Native sagebrush to irrigated pasture	2.6	2.3 x 10^7	0.04	6.3 x 10^7	0.10	1.7 x 10^8	1.17
Native sagebrush to irrigated mould-board plough	6.1	5.3 x 10^7	0.10	1.5 x 10^8	0-.25	1.9 x 10^9	2.72

[a]Land area in irrigated crop land in the Pacific Northwest is 9,055,979 ha, in the Western United States is 24,322,029 ha and worldwide is 260,000,000.
[b] % 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 x 10^{10} Mg C (C_{EW}) multiplied by 100.
[c]All data were subjected to a one way analysis of variance for a completely randomised design. Residuals were normally distributed with constant variance. Significance of treatment means were determined at $P < 0.05$ with the Least Square Means test

We used these data to calculate potential total C storage for irrigated agriculture in the Pacific Northwestern U.S. and Western U.S. over a 30 year period. If 10% of the NSB land is brought under cultivation to IMP, ICT or IP, we estimated gains of 6.0, 4.9 and 2.6 Mg C ha^{-1} respectively (Table 2). Using these values to represent C gains for all irrigated crop land in the U.S. PNW, if irrigated agricultural land were expanded by 10% and NSB were converted to IMP, a possible 5.3 x 10^7 Mg C (0.10% of total C emitted in the next 30 yr) could be sequestered in soil. If land in irrigated agriculture were expanded by 10% and NSB were converted to ICT a possible 4.4 x 10^7 Mg C (0.08% of total C emitted in the next 30 yr) could be sequestered in soil. If land in irrigated agriculture were expanded by 10% and NSB were converted to IP a possible 2.3 x 10^7 Mg C (0.04% of total C emitted in the next 30 yr) could be sequestered in soil. Using these values to represent C gains for all irrigated crop land in the western U.S., if land in irrigated agriculture were expanded by 10% and NSB were converted to IMP, a possible 1.5 x 10^7 Mg C (0.25% of total C emitted in the next 30 yr) could be sequestered in irrigated agricultural soils. If land in irrigated agriculture were expanded by 10% and NSB were converted to ICT a possible 1.2 x 10^7 Mg C (0.20% of total C emitted in the next 30 yr) could be sequestered. If land in irrigated agriculture were expanded by 10% and NSB were converted to IP a possible 6.3 x 10^7 Mg C (0.10% of total C emitted in the next 30 yr) could be sequestered. Using these values to represent C gains for all irrigated crop land worldwide, if land in irrigated agriculture were expanded by 10% and NSB were converted to IMP, a possible 1.9 x 10^9 Mg C (2.72% of total C emitted in the next 30 yr) could be sequestered in irrigated agricultural soils. If land irrigated in agriculture were expanded by 10% and NSB were converted to ICT a possible 1.3 x 10^9 Mg C (2.24% of total C emitted in the next 30 yr) could be sequestered. If land in irrigated agriculture were expanded by 10% and NSB were converted to IP a possible 1.7 x 10^8 Mg C (1.17% of total C emitted in the next 30 yr) could be sequestered.

DISCUSSION

Our results indicate that there is substantially more inorganic C sequestered in IMP than ICT or IP soils. Including inorganic C in the C budget changes results based solely on organic C for conversion from NSB to IMP, ICT or IP. Entry *et al.* (2002) found that net organic C in ecosystems decreased in the order IP>ICT>NSB>IMP. Reicosky *et al.* (1997) found that tillage increased CO^2 evolution from and decreased C concentration in mid-western U.S. soils. When including inorganic C the results change to IMP>ICT>IP>NSB. 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_3concentrations compared to rainfed areas.

Inorganic C sequestration in the U.S. in the future will be affected by conversion to sprinkler irrigation which typically requires less water, but also less leaching and spring recharge with less dissolved CO_3 in water. Well water in the U.S. PNW typically has twice the amount of dissolved CO_3 as river water. Surface irrigation requires far more water application to crops than sprinklers. 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 amount of inorganic C sequestered in soils as carbonate may not be as great as we have measured here because some of the C was already in the river water prior to irrigation and would be ultimately deposited in the ocean. Inorganic C in liquid and gas phase reactions are open phase and thus reversible. A significant amount of C may be released as warm, high pH irrigation water is mixed with lower temperature and lower pH river water. The balance of C sequestered in soils or released to the atmosphere in irrigation return flow is not well known and needs research on a watershed scale to be fully understood.

We recognise that the values for potential C gain in this 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 soils in many different vegetation types. Use of these data from Idaho provide an initial indication of the potential for these kinds of management shifts 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 world-wide uses surface irrigation, with substantial runoff resulting in some transport offsite of C via erosion with sediment and dissolved C in the water. More complete ground surveys of C balances from historical land use patterns should provide a better understanding of these processes. We see these data as an initial effort in that direction.

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