Inorganic Carbon: Land Use Impacts

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INTRODUCTION

Land use affects soil inorganic carbon, but the changes are significant only over the long term. Both increases and decreases in carbon storage occur as a result of various management practices. In irrigated lands, the primary factors causing a decrease in inorganic carbon are high leaching and maintenance of elevated water content at or near the soil surface. These factors result in elevated carbon dioxide concentrations and thus increased dissolution of soil carbonates. Use of acidifying fertilizers such as ammonia and sulfur also act to reduce soil inorganic carbon. Practices that favor accumulation of carbonates in the soil include efficient irrigation with surface waters in arid and semiarid regions (leaching less than 30% of the applied water), irrigation with ground waters at elevated CO_2 concentrations, application of gypsum to alkaline soils, and use of nitrate fertilizer. Other factors that affect soil carbonate content include land clearing, cropping practices, and erosion.

Soil inorganic carbon constitutes a major carbon pool in the near surface environment. In arid regions, the inorganic carbon can comprise more than 90% of the total C in the soil. The major inorganic C mineral phases are calcite and dolomite. Both minerals are relatively insoluble, however, dolomite dissolution is much slower than calcite dissolution at the intermediate pH values relevant to soils. Also, dolomite does not readily precipitate under Earth surface conditions. As a result, dolomite content in soils will remain constant or decrease due to dissolution, while calcium carbonate content may either increase or decrease.

LAND CLEARING AND CROPPING

Land clearing generally results in increased water runoff and soil erosion. This process or any other process such as tillage that increases erosion serves to remove the surface soil horizons. Since these horizons are generally depleted in inorganic carbon relative to less weathered, deeper horizons, there is an apparent increase in the inorganic carbon content of the surface soil as a result of erosion. In terms of carbonate dissolution the impact of land clearing is not certain.

After clearing there is increased runoff, thus decreased infiltration, favoring less dissolution of carbonates. This effect may be compensated by the decreased water consumption (lower evapotranspiration) after clearing, resulting in increased deep recharge (greater carbonate dissolution). Depending on how much biomass remains after clearing, there is likely a short-term increase in soil CO_2 followed by a longer-term reduction, favoring less carbonate dissolution in the soil. Land clearing and overgrazing in arid lands serve to increase wind erosion and to redistribute soil in the landscape. In this manner noncalcareous soils receive inputs of carbonates. This process increases net dissolution of carbonates in the landscape.

In humid environments inorganic carbon is leached from the soil. The elevated CO_2 concentrations in the soil enhance calcite solubility relative to Earth surface conditions. In humid environments carbonates are successively leached from the upper portions of the soil profile. Agricultural practices may serve to enhance or reduce the net removal of carbonates. Removal of vegetation from a site with practices such as tree harvesting or harvesting of forages serves to remove base cations and causes net acidification of the upper portions of the soil profile. If carbonates are present deeper in the soil, this acidification increases dissolution. The impact of removal of vegetation in humid environments with carbonates in the subsoil can be calculated by assuming that the net harvested alkalinity is compensated by an equal increase in carbonate dissolution in the subsurface.

FERTILIZATION

Since optimum plant growth is generally at a pH lower than that observed in untreated calcareous soils, acid fertilizers are commonly applied. Use of sulfur with subsequent oxidation to sulfate results in acid release to the soil (2 mol of protons per mole of sulfur). Application of ammonia salts, with subsequent fixation into organic matter or oxidation to nitrous oxide or elemental nitrogen, also releases protons (2 and 1 mol of protons per mole of ammonia ions, respectively). This acidification will increase carbonate dissolution proportionately, and has a significant effect since ammonia salts are widely used.

Application of urea or ammonia gas should have no net effect on carbonate dissolution (upon oxidation to nitrous oxide or elemental nitrogen). In contrast, use of nitrate fertilizers serves to increase pH and thus reduce carbonate dissolution. Generally nitrate is not utilized on calcareous soils so the impact on inorganic carbon storage in soil is slight. The quantitative impact of fertilization on changes in inorganic carbon is not easily calculated, as it depends on the extent of N incorporation into organic matter, mineralization, the extent to which the harvested biomass is removed from the site, and the occurrence of carbonates in the subsurface. The addition of liming products, primarily calcite, are reported as $3.7\,Tg\,C\,yr^{-1}$ in the U.S. for 1978.[1] This is a significant but temporary addition to the soil carbon pool as it is assumed that the majority of the material is applied to acid soils and thus it is readily dissolved.

HUMID REGION IRRIGATION

Irrigation in humid environments serves to increase the net recharge through the soils and thus should increase the removal of carbonates. These changes may be relatively difficult to detect in view of the limited amount of irrigation water added and the fact that irrigation in humid environments, although increasing rapidly, was very limited in the past. Field studies are needed to determine the impact of irrigation on changes in inorganic carbon storage in humid environments.

ARID REGION SOILS

Arid zone soils usually contain at least minor amounts of carbonates, even if classified as noncalcareous. In the absence of irrigation, there may be redistribution of carbonates within the soil but little net precipitation. The majority of the pedogenic calcite is reprecipitated calcite with relatively small amounts added as a result of mineral weathering. Significant amounts of carbonates are also added to the surface of arid land soils as dust. Calcite is leached from the upper part of the soil profile by dissolution into the infiltrating rain, and is mostly reprecipitated at depth after plant extraction of the available water.

Irrigation in arid and semiarid environments may result in a net increase or decrease in soil carbonate, depending on the water source and fraction of water applied that is leached (leaching fraction). There are two opposing effects. First, elevated CO_2 concentrations in the root zone relative to the atmospheric condition results in enhanced calcite solubility and dissolution. Second, plant water extraction and evaporation concentrate the salts into a smaller volume of water and enhance calcite precipitation. At low leaching fractions, the effect of concentration of salts due to plant water extraction and evaporation is greater than the enhanced CO_2 effect and there is net precipitation of calcite.

For a calcite saturated surface water such as the Colorado River, it is estimated[2] that at a leaching fraction of 0.1 there is net precipitation of $125\,kg\,ha^{-1}\,yr^{-1}$ of C, based on water consumption of $1.2\,m\,yr^{-1}$ and a CO_2 partial pressure of 3 kPa. Model simulations indicated that net precipitation of calcite occurred as the sum of the loss of carbonates in the upper portion of the root zone and precipitation of calcite in the lower portion. At high leaching fractions there is net dissolution of carbonates. Using a calcite equilibrium model it is predicted that at a leaching fraction of 0.4 there will be a net dissolution of carbonates of $70\,kg\,ha^{-1}\,yr^{-1}$ of C, again, based on water consumption of $1.2\,m\,yr^{-1}$ and CO_2 partial pressure of 3 kPa.[3] In all instances there is a prediction of net dissolution in the upper portion of the soil profile and net precipitation in the lower portions of the profile. Using average leaching fractions for the western U.S., it is estimated that irrigation with surface waters on 12 million ha results in an increase in inorganic carbon of $1\,Tg\,yr^{-1}$,[4] or $80\,kg\,ha^{-1}\,yr^{-1}$.

Irrigation with groundwater saturated with respect to calcite will result in precipitation of carbonates at almost all leaching fractions, since the irrigation water is equilibrated at the groundwater CO_2 partial pressure and is supersaturated upon degassing and application to the soil. Calcite saturated groundwater is used for irrigation on an estimated 3.12 million ha in the U.S. It is estimated that irrigation on these soils results in a net inorganic C precipitation of $1.3\,Tg\,yr^{-1}$ or $420\,kg\,ha^{-1}\,yr^{-1}$.[3] The above calculations are dependent on several assumptions regarding calcite equilibrium and soil CO_2 concentrations. Using a kinetic model for calcite precipitation and the measured CO_2 partial pressure in the groundwater in Palo Verde Valley there is prediction of no net change in inorganic carbon at a leaching fraction of 0.5. Consistent with these predictions the groundwater composition in Palo Verde Valley shows no evidence for net precipitation or dissolution of carbonates in the soil.

There is limited direct field evidence for the influence of irrigation on inorganic soil carbon and it is difficult to be certain that differences among sites are only related to changes in management. Researchers[4] observed a net decrease in the calcium carbonate content of three pairs of soil profiles taken from sites in Israel irrigated for approximately 40 yr as compared to nonirrigated sites. The estimated input of 4.40 m of water per year at those sites is contrasted with the yearly potential evapotranspiration of 1.93 m. The observed trend is qualitatively consistent with model predictions if we account for the input of rain and the estimated leaching fraction of 0.56. Isotopic evidence indicated that there was precipitation of

pedogenic carbonate at depth despite a net decrease in carbonate content at depth.

In a study in the San Joaquin Valley in California researchers compared samples of a soil taken from irrigated and native vegetation sites.[5] They also measured a net loss of carbonates attributed to 8 yr of irrigation. Net carbonate loss was estimated as $7 \times 10^3 \, kg \, ha^{-1} \, y^{-1}$ ($800 \, kg \, C \, ha^{-1} \, yr^{-1}$). Leaching fractions at the site were not reported but this value corresponds to approximately 10 times greater dissolution than expected based on model simulations. However, another study by the same author[6] found no change in total carbonate when comparing pedons with native vegetation and those irrigated for 5–25 yr. In this instance both gypsum and sulfur were applied as amendments for reclamation. Gypsum would tend to increase precipitation of carbonates while sulfur would acidify the soil and cause net dissolution of carbonates. In a recent, more extensive study[7] on paired soil cores (irrigated and adjacent nonirrigated sites) from the lower Colorado River basin there were no observed changes in net inorganic carbon storage after 90 yr of irrigation, and no isotopic C shifts indicative of recrystallization.

SODIC SOIL RECLAMATION

Reclamation of sodic soils can result in either an increase or decrease in inorganic carbon in the soil. Gypsum application to a sodic and alkaline soil will increase the soil carbonate content, as the increased Ca will precipitate most of the soluble bicarbonate and carbonate. Application of sulfuric acid, sulfur, or green manuring all serve to dissolve soil carbonates. Green manuring as a reclamation practice consists of incorporating plant residues into the soil and leaching with water. The high CO_2 production is combined with restricted gas transport creating very high CO_2 concentrations in the soil, dissolving large amounts of calcium carbonate. It is estimated that this process can dissolve in the order of 400–800 kg ha^{-1} during a year of reclamation. Use of acid is currently a widespread and generally recommended practice to prevent emitter clogging in drip irrigation systems. This practice may result in total removal of carbonates within 10–20 yr, for soils with less than 3% carbonate content.

IMPACT ON ATMOSPHERIC CARBON DIOXIDE

Dissolution of carbonates in neutral to alkaline environments results in consumption of CO_2 gas and formation of aqueous HCO_3^-, while precipitation of carbonates results in release of CO_2. The net effect of dissolution or precipitation of soil carbonate on atmospheric CO_2 depends on the solution flow path.

In regions irrigated with surface water the dissolution of carbonates results in a net C sink. However, the high alkalinity drainage water usually flows back to the river. The resultant degassing of carbonic acid and reprecipitation of carbonate in the river or reservoir releases CO_2 back into the atmosphere. If the water is recharged into deep aquifers the net soil flux is preserved. In acid environments, liming of soils results in CO_2 release to the atmosphere as there is little or no net alkalinity produced.

CONCLUSIONS

Land use practices have a long-term impact on soil inorganic carbon. Due to the large C pools in the soil these impacts are not generally observed in short-term studies. In humid environments the major anthropogenic impacts on inorganic C are liming of surface soils, use of NH_4 vs. nitrate fertilizer, removal of vegetation, and erosion. In semiarid and arid environments increased inorganic C is favored by the use of groundwater for irrigation and application of gypsum. Decreased inorganic C is favored by inefficient irrigation with surface water and application of NH_4 fertilizer. The net effect of irrigation on a global scale, neglecting the effects of fertilizer addition, is to increase soil inorganic C by $30 \, Tg \, C \, yr^{-1}$ as well as to release an equal amount of C to the atmosphere. Liming practices in humid regions throughout the world are estimated to have no net effect on inorganic soil C but release up to $85 \, Tg \, C \, yr^{-1}$ to the atmosphere.

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