Global Climate Change: Interactions with Soil Properties

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General Background

A quote on the walls of the Jefferson Memorial in Washington states " Soil is God's Gift to the Nation". Societies built by man have always required a rich soil together with a benign climate and the availability of water. Misuse of the soil resource has lead to the downfall of numerous civilizations when soil erosion, salinity and the silting of irrigation canals resulted in a slow strangulation of what had been a great resource (Laudermilk, 1975). The generally, highly variable climate of North America has punished us badly when we have not been good stewards of the land. Land abandonment after excess growth of cotton in the South East, the loss of soil fertility and acidification in the North East and the dust bowl of the Prairies can be attributed to the misuse of our the soil and it's organic matter. Man's success in responding to the latest challenge that of global climate change will depend on how we manage this vital resource. A proportion of the soil organic carbon (SOC) present in undisturbed soils has been burned lost through agriculture practices. This has contributed to the global rise of CO_2 in the atmosphere. However, soil organic carbon, is not a non-renewable resource; unlike coal, gas, and oil it is a renewable resource. We can put back, through proper management, much of the SOC lost (Lal, et al., 1998) and help to reduce the over all greenhouse gases.

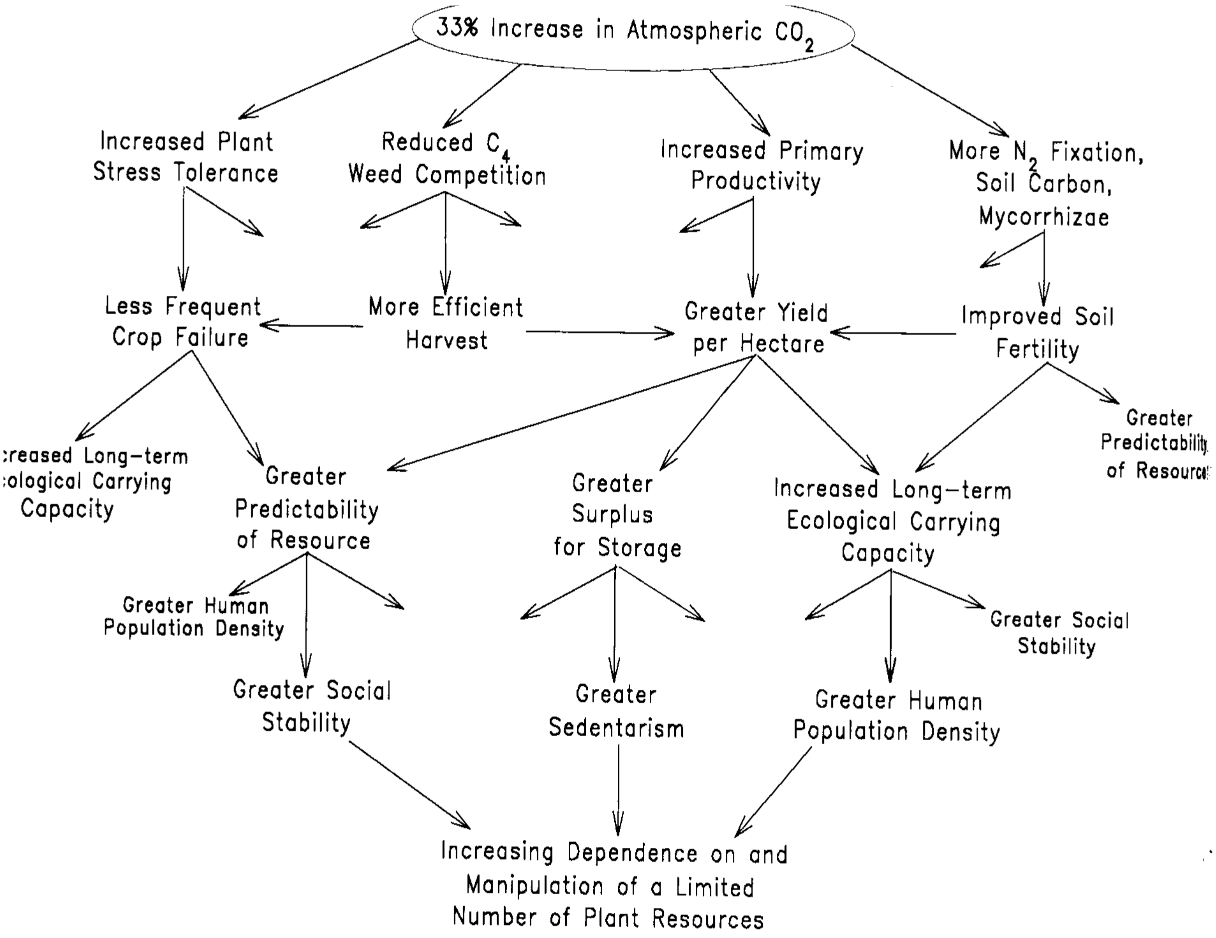
Archaeological evidence indicates that a climatic factor not often considered, the CO_2 content, has throughout history had a great influence on agriculture. The domestication of animals, 120,000 to 140,000 yr ago, is said to have occurred during a period when the atmospheric CO_2 content rose from 200 to 275 mol mol^{-1} (Sage, 1995). The domestication of plants occurred independently around the world in different cultures approximately 10,000 yr ago. Humans in the Middle East domesticated lentils, barley, chick peas and wheat. Rice, millets and the Brassica spp were domesticated in the Far East 9,000 yr ago. Beans and chili peppers were grown in Meso America 8,000 yr ago. According to Sage (1995), the factor common to these widely diverse people was global climate change and the rise in the atmospheric CO_2 from 200 to 270 ppm.

The 100 mol mol^{-1} rise in CO_2 from 270 to the present level during the last 120 yr has coincided with another explosion in crop yields. The very successful plant breeding, fertilization and better pest control would not have been as effective if the major plant nutrient, i.e., carbon had not been increasing during this time. The mechanisms by which increased CO_2 affects humans, shown in Fig. 1, play as great a role today as they did 10,000 years ago.

The elements carbon and nitrogen oxygen and hydrogen are the building blocks of life on earth. They also are the most important constituents of soil organic matter. The earth's carbon and nitrogen cycles have the ability to restore and even increase the soils organic matter content, improve fertility, increase the water holding capacity, and improve tilth if properly established scientific principles are applied to good land stewardship and sustainable agriculture.

Global change scenarios are most often associated with the predicted increases in temperature and climate instability associated with increased atmospheric concentration of gases of carbon and nitrogen. These radiative gases, or greenhouse gases, consist of CO_2, CH_4, and N_2O produced by microbial activities in soils, sediments, surface waters, animal digestive systems, plant respiration or through the burning of fossil fuels. Soil microorganisms upon breaking down plant and animal residues in environments containing oxygen produce CO2. This returns to the air the carbon that has been fixed by photosynthesis and in the past has kept the carbon cycle in near balance. In areas where oxygen is lacking such as in peat bogs, rice fields and the stomachs of ruminants, methane (CH_4) is produced instead of CO_2. The radiative gases in the past have kept the earth's average temperature at a livable 15° C rather than the frozen-18° that would occur in their absence.

Figure 1. Possible linkages between an increase in atmospheric CO_2 from 200 to 270 mol mol^{-1} and increased human specialization on a limited number of plant resources. (From Sage, 1995)



Soil inorganic nitrogen is produced when microorganisms “burn off” the carbon of plant and animal residues or organic matter in their never ceasing search for energy. Other microorganisms oxidize, by the nitrification process, the inorganic N that is produced on mineralization or added as fertilizer. This process is leaky and produces N_2O. The oxidized form of nitrogen, NO_3, produced during nitrification can again be reduced under anaerobic processes where there is no oxygen. This process is again leaky and can result in N_2O leakage to the atmosphere.

Methane (CH_4) is 20 time as reactive as CO_2 in retaining atmospheric heat. The gas N_2O is 300 times as reactive. The relative effect of these in causing greenhouse effects is best seen by expressing the emissions as carbon equivalents. In the mid 1990’s (US EPA 1995), the USA released 1,450 Tg (million metric tons (MMT) of carbon into the atmosphere from fossil fuel consumption. This is less than one tenth that which is released annually from our soils by decomposition but the carbon of decomposition is offset by a nearly equal amount of photosynthesis while the equivalent of about one half that formed from fossil fuels accumulates in the atmosphere.

A total of 180 Tg of CH_4 equivalents are released from transportation, industry, wetlands, landfills and waste. Aerobic, terrestrial sites all generally absorb CH_4 but cultivated, fertilized soils consume only about one quarter that of undisturbed sites and wildlands. Agriculture is the predominant source of N_2O with transportation and industry supplying about as third as much as does agriculture. All soils release some N_2O but highly managed ones release more than do wildlands especially if they have trees. The gas CO_2 is presently increasing in the atmosphere at 0.5% per year, CH_4 at 0.75% and N_2O at 0.75%.

The clearing of forests, draining of wetlands and the cultivation of the both prairie and forest soils for agriculture lead to significant increases in atmospheric CO_2 as organic carbon in the soil and above ground biomass was decomposed. The carbon content of most agricultural soils is now about one third less than that in its native condition as either forest or grassland. Fortunately, modern agriculture has stopped this net loss to the atmosphere (Bruce et al., 1998). This has come about through higher levels of biomass production, the return of greater proportions of the crop residue to the land, use of cover crops and conservation tillage such as reduced and no till (Lal et al., 1998). The return of considerable acreage to grass or forests in conservation reserve programs (Conservation Reserve Program (CRP) and Wetlands Reserve Program (WRP) and to trees in afforestation of formerly cultivated lands is also returning atmospheric CO_2 to the land. It is considered that the Eastern USA now has 110 million acres of afforested lands once in agriculture that are now storing carbon (Fan et al., 1998). This occurs both as tree growth and in increased soil organic matter contents. The other greenhouse gases, CH_4 and N_2O can also be removed from the air by soil microorganisms. Improved pastures and cover crops on cultivated land lower the amount of inorganic N in soil and can lower atmospheric radiative gases. Higher quality cattle feeds can reduce CH_4 emissions from domestic livestock. Better fertility management through soil testing, precision farming, and proper nutrient application can also lead to lowering of greenhouse gas emissions.

Soil-Biological and Chemical Interactions in Global Change

There are a large number of agronomic-ecological interactions that occur in a world with increasing levels of CO_2, higher temperatures and a more variable climate. There is great diversity of soil organisms many of which have similar functions and general decomposition reactions. This makes it possible to predict future effects of changes in soil temperature and moisture on the basis of overall controls that apply to most soil types within a major climatic area. Climate change and the accompanying extreme events will no doubt alter soil microbial populations and diversity. Given time the populations of soil biota should adapt but cataclysmic occurrences such as floods and erosion will affect the diversity of microbial populations in local areas.

The CO_2 content of soil is higher than that of the atmosphere; atmospheric concentrations of CO_2 are not expected to directly alter soil nutrient cycling. The indirect effects however have to be considered. Because of more available substrate, the symbiotic partners consisting of nitrogen fixers such as the rhizobia and the mycorrhyzal fungi should be able to obtain a greater food supply and grow more effectively with a consequent benefit to the plant. This will be especially important in forests and native grasslands, that are not normally fertilized, as they adapt to global change.

Plants are more sensitive to temperature changes than are microorganisms. Increased temperature will move the growth capabilities of specific plants 200 to 300 km north for each degree Celsius rise in temperature. This is equivalent to 60 to 90 miles for each degree Fahrenheit. This together with breeding for cold tolerance is now moving the Corn Belt into the Prairie Provinces of Canada. Insect activity of cold-sensitive insects has been observed to move northward with even the slight rise in measured temperatures. With increased temperatures, we can expect to see cold-sensitive tropical and subtropical soil pathogens and weeds as well as fire ants in areas of what is now the Corn Belt.

Many soils contain inorganic carbon as carbonates. The pedogenic phases of these compounds can both release and sequester CO_2. Applications of nitrogenous fertilizers is acidifying in nature and on some soils results in the need for the addition of lime that on solubilization releases CO_2 to the atmosphere. In addition, CO_2 is released from calcareous soils when nitrogen fertilizers are applied and subsequent microbial activity releases hydrogenions. Calcium is added as lime in dust and during the weathering of parent materials. This reacts with CO_2, based on the carbonate-bicarbonate (HCO_3-) reactions, to produce carbonates. Batjes (1996) and Eswaran (et al., 1993) estimate that soil inorganic carbon comprises approximately 700 Pg C in the surface layers; this is one half that usually estimated for organic C. Soil inorganic carbon is being leached out of soils at an estimated rate of 0.25 Pg per year whereas rivers are thought to transfer 0.42 Pg C to the oceans annually. This provides a net CO_2 sink (Nordt et al., 1999) that also must be considered.

Although irrigation waters releases some trapped CO_2, it is estimated that on a world wide basis irrigated soils because of their high production of crop residues sequester 0.16 to 0.27 Pg C yr^{-1} of atmospheric CO_2 (Holland, 1978; Bouwman and Lemans, 1995). Soil formation will be slowly altered by changes in moisture and temperature. The US is now receiving 10% more rainfall than in previous decades. Higher moisture and temperature will result in deeper, more leached soil profiles with clay eluviation to lower horizons. These effects are slow and will be over shadowed in the near term by changes in management or erosion. Wind and water erosion can cause local extreme climatic and storm events. Agriculture has drastically changed since the dust bowl of the 1930's, but special precautions must be taken in susceptible areas when multiple year droughts with associated poor crops and high winds will again create the conditions for possible severe wind erosion whether or not this is associated with specific climate change events.

Flooding affects both agricultural and non-agricultural areas. For example, a wetter climate is expected in California with increased temperatures and more oceanic evaporation. Massive soil movement, as in soil slippage, and local flooding will be increased by more severe, local storms. Lal and Bruce (1999) estimate that 0.5 Pg C yr^{-1}

are lost from local soils by erosion. Much of this is deposited within associated landscapes but 20% of this is thought to be lost to the atmosphere through accelerated decomposition. The fate of the transported carbon however is not well-known and recent estimates (Trimble, 1999) show that recent water erosion is only on sixth that which occurred during the early years of agriculture in the US Midwest.

Erosion and leaching can move extensive nutrients to rivers and eventually to estuaries. The nutrients, especially nitrogen and phosphorous, can create local high nutrient levels and thus anoxic events with serious pollution and local fish kills. This is now the case in areas such as the Mississippi Delta and Gulf of Mexico as well as in the Chesapeake Bay. The contribution of agriculture to such pollution must be determined. Possible nutrient losses in a climate-change scenario must also be considered. Nutrient management will have to include lower inputs and more timely applications of nitrogen and phosphorus and more containment of local floodwaters so the nutrients can soak back into the land. The effects of extensive concentrations of both human and animal waste products on small land areas or in lagoons also must be considered. This removes nutrients from the areas where crops are grown and often concentrates them in erosion and flood-prone areas. This creates the potential for the contamination of surface and subsurface waters if flooding and erosion are increased with climate change.

Soil Organic Matter and Global Change

Organic matter constitutes from 1 to 8% of the weight most soils and nearly all the dry weight of organic soils such as peats. Because of the great weight of soils to the plant rooting depth at which carbon accumulates, the soils of the world store about 1600 Pg of carbon. This represents a carbon storage capacity that is twice that in the atmosphere. The annual global rate of photosynthesis is generally balanced by decomposition and represents one tenth of the carbon in the atmosphere or one twentieth of the carbon in soils. The US account for about 5% of this storage, Canada because of its higher proportion of peat soils accounts for up to 17% (Lal et al., 1998).

Soil organic carbon is composed of a wide range of compounds that decompose at different rates depending on their chemistry, soil temperature and moisture, organisms present, association with soil minerals and the extent of aggregation (Paul et al., 1996). Plant residues in agricultural soils do not represent a large storage pool; however, their management influences water penetration, wind and water erosion and the extent of formation of soil organic matter thus affecting long term soil fertility and carbon storage.

Decomposition by soil organisms is relatively insensitive to dryness when examined on an annual basis.   Most soils have some periods of time when decomposition can occur. Decomposition however is very sensitive to excess wetness that causes anaerobiosis. This in the past has created the high, organic matter peat soils. Changes in moisture content have resulted in increased decomposition of soil organic matter when the millions of acres of wetlands in the Corn Belt were tile drained (Lal et al., 1998). Warmer temperatures are often associated with drier climates. This has been postulated to greatly affect the peat soils that contain so much of North America's soil organic carbon. The drying of peat soils to below water saturation would greatly increase decomposition rates and CO_2 evolution to the atmosphere. Water saturation of soils is as much, if not more, controlled by drainage and topography as by rainfall and temperature. Predictions based on temperature-rainfall alone will not necessarily be valid relative to decomposition in peats. It is possible to control soil moisture of tile drained soils in the winter by controlling (plugging) tile drainage flows. This creates temporary wetlands and thus retards decomposition. It should have the further benefit of decreasing nitrates and possibly pesticides in the ground water as well as helping in flood control. Wetland restoration in general has potential for future carbon sequestration, providing greater diversity and havens for wildlife and reducing nitrates in ground water. It however will lead to some increases in $_{CH4}$ and possibly N_2O evolution from the flooded soils.

Grasslands contain approximately one fifth of the world's global carbon reserves; many of the world's grasslands have been degraded by overgrazing. This has resulted in a loss of plant cover less protection against wind and water erosion and loss of production potential. Soil organic matter degradation in such conditions has contributed to the rise in atmospheric CO2. Grazing and other management practices that lower overgrazing have the potential to increase global carbon sequestration substantially (0.46 Pg C yr^{-1}). This should also result in more CH_4 utilization. Improvement of the cattle's diet should result in less CH_4 production by the cattle. Fertilizer nitrogen is one of the suggested means, together with better grazing management, of increasing grassland production and soil carbon sequestration. The production of the fertilizer nitrogen however utilizes fossil fuels and its application could lead to more N_2O evolution. The closer coupling of grazing with intense animal feeding operations such that nutrients are returned for pasture improvement would great reduce problems with pollution when excess rainfall causes flooding.

The increased CO_2 in the atmosphere has made it possible to greatly increase yields through plant breeding, fertilizer additions and pest control. The continued predicted increase in plant of 1.25% per year (Reilly, 1996) will produce a similar increase in the crop residue applied to the soils. At equivalent nitrogen levels, there will be a production of more carbohydrates and possibly more lignin and polyphenols. The polyphenols should slow down decomposition rates and help build organic matter. The changed composition of leaves and roots will affect the insects and microbiota feeding on the plant parts. These are a part of a complex foodwebs, often involving numerous layers of predators; the insect response of CO_2 should be considered in climate change scenarios.

The large size of the soil carbon pools and their slow turnover rate means that they are fairly well buffered against change and that short term effects unless they involve erosion, and thus removal of carbon from the landscape, do not have immediate effects. It usually takes 5 to 10 years of altered management to produce measurable increases in carbon and the associated soil fertility and soil tilth. However, losses can be much faster under improper management. The large size of the carbon pool and the fact that soil carbon is very unevenly distributed across the landscape makes it difficult to accurately measure changes that occur over a few years.

Calculation of soil carbon sequestration for research purposes is best based on long-term plots that have been under a specific management scheme for 10 to up to 30 yr. Soil fractions that are sensitive indicators of soil carbon changes over shorter periods are best used in conjunction with modeling that is based on a knowledge of the controls on soil carbon dynamics (Fig. 2). This makes it possible to predict the effect of specific management to other soil types and landscape areas where policy decisions need to be made. Indicators that have been found useful include the light fraction obtained by floating soil in water or a more dense liquid. This reflects partially decomposed plant residues that make up a portion of the active fraction of soil organic matter. The microbial biomass that feeds on the residues and on the active and slow fraction of soil organic matter is another measurable fraction that changes rapidly enough to be an indicator of total changes.

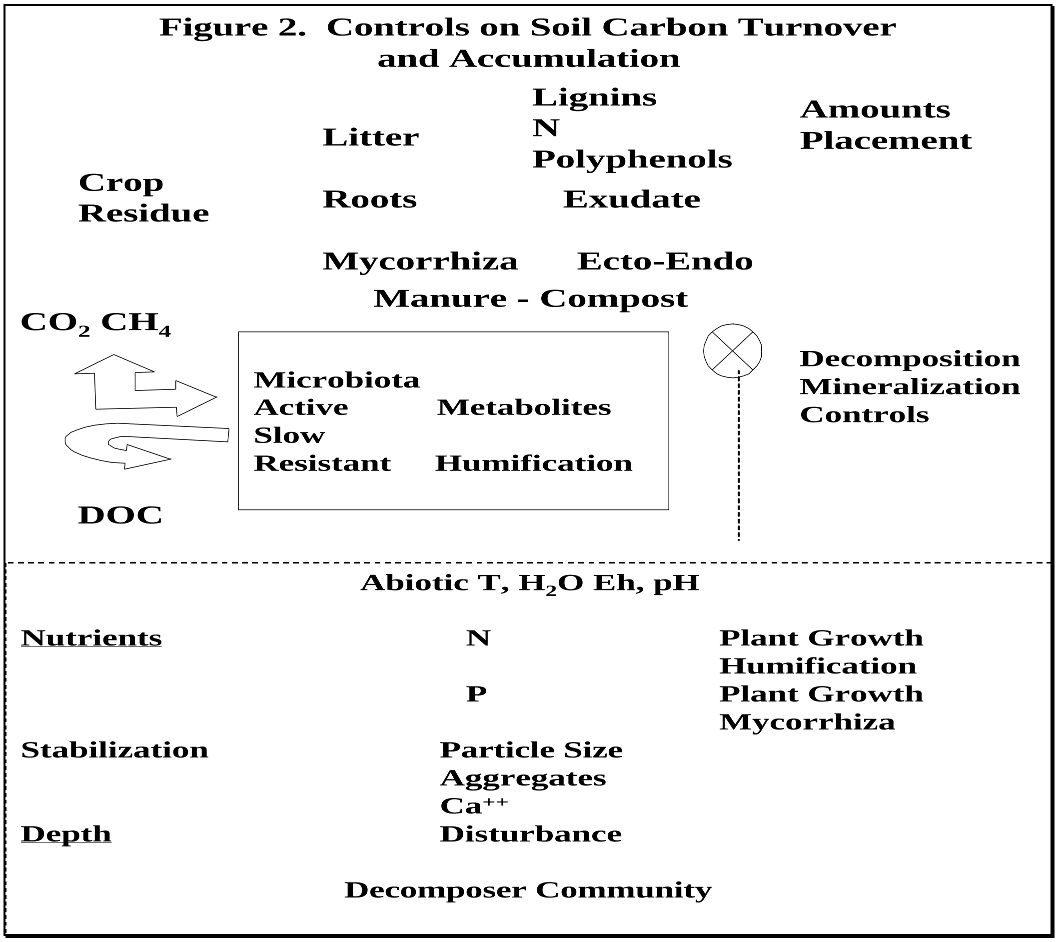


Figure 2. Controls on Soil Carbon Turnover and Accumulation

The partially altered plant materials that are held within aggregates and thus slowly decompose over a period of years constitute part of the slow release fraction that is so essential to soil fertility. This fraction known as particulate organic matter can be measured by disrupting the aggregates and has potential as an indicator of the overall size of the slow pool both in management for sustainable agriculture and in carbon sequestration calculations. Incubations, in the laboratory, of soils from various management treatments on different soil types and under representative climatic conditions makes it possible for the soils natural population of soil fauna and soil microorganisms to decompose the differently available fractions over time. Analysis of the CO_2 evolution curves determines the size and turnover rate of the active and slow fraction if the size of the resistant pool has previously been determined by acid hydrolysis.

The above biophysical techniques are best utilized on well documented and characterized, long-term plots with known management histories where total carbon and soil bulk density can be measured to the rooting depth. If these plots are representative of the different soil types climate and management it is possible with mathematical models such as the Century (Coughenour and Parton, 1996) or TEM (Melillo et al., 1993) to predict carbon levels for policy decision making. The continuation of research on the long-term plots together with measurements on an array of well distributed validation plots as well as of individual management systems would make it possible to plan new approaches and to support policy decisions that must be made as we adapt to global change.

Soils in a North American Context

The warming of North America is already noticeable in the increased growing seasons and the northward movement of the limits of corn and soybean seed production growth. The Corn Belt will thus move into the Canadian Prairies. The soils of northern parts of Minnesota, Wisconsin, Michigan, New York, Vermont, and Maine would increase in importance. The rocky, exceptionally sandy and hilly soils in such areas may better be left in trees both from an agroforestry viewpoint and from the aspect of removing of the carbon from the atmosphere. Canada does not have a great deal of potentially useful agricultural land in the East unless it becomes so warm that the Hudson Bay lowlands could be suitable for agriculture. Warming of Western Canada will produce more potential agricultural land. Alberta and Northern British Columbia could develop significant underutilized acreage that however would be far from markets.

Sandy soils are much more sensitive to climatic fluctuations than the loam and clay soils. Fortunately many of the drought sensitive, sandy soils of the Great Plains have already been removed from cultivation. It is important that public policy as well as management by individual operators continue to protect these fragile soils. The extent and distribution of rainfall is the greatest unknown in future climate scenarios. It is predicted that because of higher temperatures there will be more moisture in the atmosphere and thus more rainfall on land. What is not known is where this moisture will fall. Warm periods have generally been associated with drought on the prairies. If this continues to be the case, the increased decomposition of soil organic matter due to higher temperatures will be somewhat offset by decreased decomposition due to lower moisture.

Field Validation

The overall requirements for soil organic matter research and field validation of the role of soil carbon in global change are:

1) Provide the analytical background and knowledge concerning the effects of agronomic management on different soil types to predict and model their effect on soil organic matter contents and other green house gases.

2) Establish benchmark sites, on a national level, that can provide verification of treatment effects. This requires field measurements, under different management, on the soil types and climates representative of most of agricultural production with enough accuracy that possible future CO_2 emission credits can be validated.

3) Provide national inventories of soil carbon storage and the fluxes of CO_2, N_2O and CH_4 into and out of soils.

4) Participate with available informational systems such as industry consultants and university and government extension systems to provide the necessary information to the public and the agricultural industry concerning the present and future role of soils in global change.

Adapting to Global Change: Policy Implications

Agriculture has had and will continue to have the ability to adapt to new scenarios. The ability to change with a changing climate will depend on a strong research base that can supply the required information. Some of the areas that may benefit the most include:

1) Crops vary in their response to enriched CO_2 in a number of growth characteristic. Research utilizing plant breeding and molecular techniques in conjunction with studies of physiological responses to increased CO_2 would increase productivity and could also lead to changes in the lignin content of plants. It may also result in increased crop residue additions to the soil. The improved soil organic matter levels will sequester CO_2, enhance sustainability and reduce soil erosion. Similar techniques could be used to produce plants with increased roots and biological nitrogen fixation as well as plants with higher capacities to take up nutrients through more efficient mycorrhyza.

2) Increased phenolic and lignin contents of plant residues could decrease decomposition rates and result in more crop residues at the surface. They should also enhance the formation of the slow and resistant carbon pools important to carbon storage. The growth of more perennial crops could have many benefits especially when utilized as a biological, non-fossil fuel energy supply.

3) Irrigation efficiency should be improved. Increased oceanic temperatures should result overall in more rainfall. This can be more efficiently utilized by drip irrigation, water harvesting, and etc.

4) Develop more efficient nitrogen and phosphorus fertilizer usage, especially in flood prone areas. Precision farming holds promise for better nutrient control and pesticide application. The nitrogen, phosphorus, sulfur and carbon cycles need to be considered in an ecosystem context.

5) The movement of intensive animal feeding operations to the source of the animal feeds and away from some extensively populated areas would enhance the placement of nutrients and organic residues back on the soil and could help to stop the development of these animal feeding facilities on flood prone areas also needs to be further discouraged.

6) Increased soil organic matter will store more atmospheric carbon and result in greater soil fertility, better soil tilth, greater water holding capacity, and reduced erosion. It also will make plants more stress resistant and thus able to better withstand the greater predicted climatic fluctuations.

7) Control of water levels on hydric soils during periods of non-plant growth could result in C sequestration, improved water quality, flood control and better wildlife habitat. Potential losses of CH_4 and N_2O would have to be avoided.

8) Soil pathogen and pest control in a warmer, often more humid climate would have to be considered in future management scenarios.

9) Improved range and pasture (or use grazing land) management would result in carbon sequestration.

10) Integration of farm woodlots, buffer strips, grass water ways, and riparian strips into overall land management and farm policy programs would enhance both water quality and a positive response to global change.

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