Use of Simulation Modelling in Climate Change Research: Special References to natural Resource Management

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3-12 OCTOBER, 2012

Division of Soil Physics
Indian Institute of Soil Science
Nabibagh, Berasia Road, Bhopal-38 (MP)
Training Manual

Short Course

on

Use of Simulation Modelling in Climate Change Research: Special Reference to Natural Resource Management

3-12 October, 2012

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Foreward

Recently, the profitable crop production with the simultaneous maintenance of quality of the environment has become an important issue that agricultural scientists and producers must address. They are required to formulate strategies for optimizing the profitability of crop production while maintaining soil quality and minimizing environmental degradation. Therefore, the management of natural resources has gained attention in context of climate change. Solutions to this new challenge require consideration of how numerous components interact to effect plant growth. To achieve this goal, future agricultural research will require considerably more effort and resources than present research activity.

The natural resource management is an important aspect in agricultural production. In the present context of climate change, there is possibility of decrease in crop yield in tropical and subtropical agriculture in future. Climate change through its climate variability and climate forcing not only affects crop production but also affects the movement of water and nutrients in soils. Carbon sequestration in agricultural soils is also liked to be affected by climate change. Advances in computer technology have made possible the consideration of the combined influence of several factors and processes to quantitatively combine the soil, plant, and climatic systems to more accurately predict crop yield. Thus, it has become possible to simulate various processes that govern crop yield. With the help of simulation models, it is possible to simulate various aspects of climate change in crop production. Thus, a crop growth simulation model not only predicts the final state of total biomass or harvestable yield, but also contains quantitative information about major processes involved in the growth and development of a plant. Thus, a sophisticated crop model can simulate the effects of weather, soil water, and nitrogen dynamics in the soil on growth and yield for the specified cultivar. To name a few, DSSAT, APSIM, CropSyst, AGROSIM and InfoCrop etc are some of the models used for crop growth simulation study.

Today, world is facing some long term substantial deviation from present climate because of variations in weather and climatic elements due to some natural and anthropogenic activities/phenomena. The variability of our climate and especially the associated weather extremes is currently one of the concerns of the scientific as well as general community. The application of crop models to study the potential impact of climate change and climate variability provides a direct link between models, agro-meteorology and the concerns of the society. Thus, knowledge-based systems-approach research will gradually increase in importance relative to experience-based conventional agronomic research. Crop models will become an important mechanism for synthesizing the existing knowledge about plants and natural resources and for updating this knowledge as we learn more about complex agricultural systems. Thus, this ICAR Sponsored Short Training Course on “Use of Simulation Modelling in Climate Change Research: with Special Reference to Natural Resource Management” is a step in right direction. Hope this training programme will serve many purposes for the scientific communities for which it has been intended.

Director, Indian Institute of Soil Science, Bhopal
Acknowledgements

It is special privilege to write acknowledgement about the ICAR sponsored Short Training Course on “Use of Simulation Modelling in Climate Change Research: with Special Reference to Natural Resource Management” held during 3rd to 12th October 2012. First I would like to thank the Director of Indian Institute of Soil Science, Bhopal for his help in formulating such type of Short Course which we don’t get many chances to see on national level. Secondly, I would like to thank my Course-Co- Director, Dr. Sangeeta Lenka and Dr. R. S. Chaudhary, Course Co-Director for their support and help in formulating as well conducting this training course smoothly. Thirdly I would like to thank our honourable DDG (NRM), Dr. Anil K. Singh in gracing the inaugural session of the Training Course as Chief Guest. We all the course directors sincerely thank Indian Council of Agricultural Research for supporting grants for this training course.

Our sincerely thanks are also due to the administrative staffs (AO, AAO, AFAO and other supporting staffs) of Indian Institute of Soil Science, Bhopal for their help in carrying out the office work in time. We are also thankful to the Director, CIAE Bhopal Dr. Pitam Chandra, Co-ordinator Guest House Dr. M. K. Tripathy and I/C of ITC and Guest house for their support in arranging boarding and lodging for the trainees. We are thankful to I/C AKMU, Dr. Somasundaram, Director Cell and I/C Traing hostel at IISS, Bhopal for their support. We can’t forget all the scientists of Division of Soil Physics, other staffs namely Mr. R. K. Mandloi, Mr. P. K. Chauhan and Mr. Darash Ram for their help in conducting the Training.

Special mentioned goes to Dr. Nishnat K. Sinha for his help and time he spent for this training programme and also Dr. Brijlal Lakaria Principal Scientist, Division of Soil Chemistry and Fertility for his help. We are also thankful to all the HODs and PCs of this Institute for their support. Over and above I thank my family and Almighty for giving me strength and support for this Training Programme. Thank you all.

(M. Mohanty)
Scientist (SS) and Course Director
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Climate change

Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (Ministry of Environment and Forest, Government of India, website). Greenhouse gases (for example, carbon dioxide, methane, nitrous oxide, water vapour, ozone), are the gases that are present in very small quantities in the atmosphere that absorb the heat radiated from the earth’s surface to the atmosphere and thus emit some of the heat to the earth’s surface. If they did not perform this useful function, most of the heat energy would escape, leaving the earth cold (about -18 °C) and unfit to support life. Due to Industrial growth in recent times, the atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have grown by about 31%, 151% and 17%, respectively, between 1750 and 2000 (IPCC 2001). An increase in the levels of GHGs could lead to greater warming, which, in turn, could have an impact on the world’s climate, leading to the phenomenon known as climate change. Indeed, scientists have observed that over the 20th century, the mean global surface temperature increased by 0.6 °C (IPCC 2001). The inter-governmental panel on climate change has projected that the global mean surface temperature is predicted to rise by 1.1–6.4°C by 2100 (IPCC 2007).

Climate change effects on crops

Increased carbon dioxide levels in the atmosphere as a result of climate change will alter global temperatures and rainfall amounts. These factors will influence how well plants grow and affect food production. Higher temperatures cause heat stress in plants. This means they grow less and produce fewer crops. In some cases, the plants do not reproduce at all since excessive heat causes sterility of the pollen (the masculine reproductive part of the flowers). A temperature increase may be beneficial in areas which are very cold at present. For example, in Siberia or Northern Europe it may, in the future, be possible to grow crops for longer periods of the year. But in tropics and subtropics the things will go worse and will be affected much more in terms of crop production than the cold temperate areas. Changes to our climate are happening more quickly now than they have ever done before in the geological past. Plants will have to adapt to new climate conditions more rapidly than they have ever had to do so before.

Water availability directly affects the growth of plants and how much crop they produce. Excessive rainfall results in floods. Waterlogged soil causes plant roots to rot and heavy rainfall damages tender young plants. Increased rainfall without flooding may be beneficial in very dry areas and allow limited crop growth. So changes in temperature and precipitation patterns as a result of climate change are likely to be bad for large areas of the world but may increase crop production in other regions. However, one of the likely outcomes of climate change is also an increase in the severity of rain storms and droughts and both of these are likely to have large and devastating effects on agriculture.

The increase in atmospheric carbon dioxide (CO2) levels resulting from fossil fuel combustion has a fertilizing effect on most plants since CO2 is needed for photosynthesis (the biochemical mechanism of plant growth). Photosynthesis converts carbon dioxide and water into the simple sugar glucose and emits oxygen, making it possible for animals to live on Earth. Scientific experiments have shown that increasing atmospheric CO2 levels leads to an increase in plant growth. Therefore, that increases in CO2 emissions from fossil fuel combustion are a good thing for crop growth and can have a positive influence on photosynthesis; under
optimal growing conditions of light, temperature, nutrient and moisture supply, biomass production can increase, especially of plants with C₃ photo-synthetic metabolism, above and even more below ground. However, the negative effects of climate change are usually much larger than the positive ones. Even though, increase in ambient CO₂ does not have significant direct effects on C₄ (C₄ carbon fixation pathway) photosynthesis of maize crop (Leakey et al. 2004, 2006), increase in ambient CO₂ leads to higher water use efficiency in water stress conditions and there by directly influences dry matter production and grain yield (Leakey et al. 2004).

The various studies have shown that climate change scenarios decrease simulated yields in many cases, while the direct effects of increasing atmospheric CO₂ mitigate the negative effects primarily in mid and high latitudes. The differences between countries in yield responses to climate change are related to differences in current growing conditions. At low latitudes, crops are grown nearer the limits of temperature tolerance and global warming may subject them to higher stress. In many mid and high latitude areas, increasing temperatures may benefit crops otherwise limited by cold temperatures and short growing seasons in the present climate. Under the estimated effects of climate change and atmospheric CO₂ on crop yields, world cereal production is estimated to decrease between 1 and 7% depending on the GCM climate scenario. The largest negative changes are predicted in developing countries, averaging −9% to −11%. By contrast, in developed countries production is estimated to increase under all but the UKMO scenario (+11% to −3%). Thus existing disparities in crop production between the developed and developing countries are estimated to grow (Figure 1) (Parry, 2007).

![Fig. 1. Cereal crop production in the world under different climate change scenarios](image)

### Climate change effect on soil processes

Soils, as a medium for plant growth, would be affected in several other ways. Increased temperatures may lead to more decomposition of soil organic matter;

1. Increased plant growth due to the CO₂ fertilization effect may cause other plant nutrients such as N and P to become in short supply; however, CO₂ increase would stimulate mycorrhizal activity (making soil phosphorus more easily available), and also biological nitrogen fixation (whether or not symbiotic). Through increased root growth there would be extra weathering of the substratum, hence a fresh supply of potassium and micronutrients;
2. The CO$_2$ fertilization effect would produce more litter of higher C/N ratio, hence more organic matter for incorporation into the soil as humus; litter with high C/N decomposes slowly and this can act as a negative feedback on nutrient availability;

3. The 'CO$_2$ anti-transpirant' effect would stimulate plant growth in dryland areas, and more soil protection against erosion and lower topsoil temperatures, leading to an 'anti-desertification effect'.

**Climate change and insect-pest diseases and weed growth**

Climate change has the potential to modify host physiology and resistance, as well as to alter stages and rates of development of the pathogen. Elevated concentrations of CO$_2$ are believed to result in a denser plant canopy. When it is combined with increased humidity, it is likely to promote foliar diseases such as rust, powdery mildew, leaf spot and blights (Råberg, 2008). Moreover, there will be most likely shift in the geographical distribution of host and pathogen. The mechanism of pathogen dispersal, suitability of the environment for dispersal, survival between seasons and changes in host physiology and ecology in the new environment will largely determine how quickly pathogens become established in a new region. Elevated winter temperatures are likely to give higher survival rate for the aphid, which can reproduce early and severe the virus incidence. Changes may occur in the type, amount and relative importance of pathogens affecting a particular crop. It would be more pronounced for pathogens with alternate hosts. Durability of plant resistance may be affected as pathogens will have more time to evolve aggressive races.

Global warming and other climatic changes will affect weed growth, phenology, and geographic distribution in a similar way as for the main crops. Higher CO$_2$ concentration will stimulate photosynthesis and growth in C$_3$ weed species, as well as increase water use efficiency in all weed species. Increased rhizome and tuber growth in perennial C$_3$ weeds is a likely response to elevated CO$_2$ concentrations. Thus it would be more difficult to control perennial weeds mechanically as well as chemically. As an increased winter temperature facilitates wintering of insect populations, the effectiveness of biological control of weeds could increase.

**Adaptation and mitigation**

**Types of Adaptation Options in Agriculture with special reference to natural resource management**

Agricultural adaptation option with special reference to natural resource management is the technological developments. The main types of adaptations are summarized in Table 1 with examples.

**Table 1. Adaptations to climate change**

**A. Technological developments**

<table>
<thead>
<tr>
<th>Crop development</th>
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<tr>
<td>Develop new crop varieties, including hybrids, to increase the tolerance and suitability of plants to temperature, moisture and other relevant climatic conditions.</td>
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<th>Weather and climate information systems</th>
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<tr>
<td>Develop early warning systems that provide daily weather predictions and seasonal forecasts.</td>
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<tr>
<th>Resource management innovations</th>
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<tbody>
<tr>
<td>Develop water management innovations, including irrigation, to address the risk of moisture deficiencies and increasing frequency of droughts.</td>
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<tr>
<td>Develop farm-level resource management innovations to address the risk associated with changing temperature, moisture and other relevant climatic conditions.</td>
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B. Farm production practices

**Farm production**

Diversify crop types and varieties, including crop substitution, to address the environmental variations and economic risks associated with climate change.

Diversify livestock types and varieties to address the environmental variations and economic risks associated with climate change.

Change the intensification of production to address the environmental variations and economic risks associated with climate change.

**Land Use**

Change the location of crop and livestock production to address the environmental variations and economic risks associated with climate change.

Use alternative fallow and tillage practices to address climate change-related moisture and nutrient deficiencies.

**Land topography**

Change land topography to address the moisture deficiencies associated with climate change and reduces the risk of farm land degradation.

**Irrigation**

Implement irrigation practices to address the moisture deficiencies associated with climate change and reduce the risk of income loss due to recurring drought.

**Timing of operations**

Change timing of farm operations to address the changing duration of growing seasons and associated changes in temperature and moisture.

C. Farm financial management

**Crop insurance**

Purchase crop insurance to reduce the risks of climate-related income loss.

**Crop shares and futures**

Invest in crop shares and futures to reduce the risks of climate-related income loss.

**Mitigation measures**

There is an extensive list of technically possible options for mitigating emission in agriculture and land-use. Measures may be categorised as: reducing emissions via improved farming efficiency, including genetic improvement; displacing fossil fuel emissions via alternative energy sources; and enhancing the removal of atmospheric CO₂ via sequestration into soil and vegetation sinks. Some mitigation options, typically current best management practices, deliver improved farm profitability as well as lower emissions and thus might be adopted without government intervention beyond continued promotion/revision of benchmarking and related advisory information services.

**Table 2. Mitigation measures affecting adaptation in agricultural systems**

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<th>Mitigation measures</th>
<th>Adaptation issues</th>
<th>Soil erosion control</th>
<th>Nutrient loss reduction</th>
<th>Soil and water conservation</th>
<th>Genetic diversity</th>
<th>Micro-climate modification</th>
<th>Land use change</th>
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</thead>
<tbody>
<tr>
<td>Catch crops</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Reduced tillage</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Residue management</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
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<td></td>
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<tr>
<td>Extensification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Fertilizer application</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fertilizer type</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Rotation species</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
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</table>
Adding legumes  +  +  +  
Permanent crops  +  +  +  
Agro-forestry  +  +  +  

Source: Adapted from Oleson and Porter (2009).

Oleson and Porter (2009) summarise the effects of a range of mitigation measures on six main factors relevant to adaptation in agriculture (with a particular focus on arable systems). Some of these are shown in Table 2, which is not exhaustive but shows some examples of where mitigation measures can have positive (or negative) implications on the adaptive capacity of a system. Mitigation measures generally aim to reduce nutrient losses in the system. This is mainly achieved through increasing the nutrient and water retention in the systems and preventing soil degradation, which also helps to make the system more resilient to droughts and flooding. Similarly, adaptation actions can affect mitigation efforts, particularly those that reduce soil erosion, leaching of nitrogen and phosphorus; those that conserve soil moisture; those that increase the diversity of crop rotations; those that modify the microclimate to reduce temperature extremes and provide shelter, those that involve land-use change, involving the abandonment or extensification of existing agricultural land or the cultivation of new land (Oleson and Porter, 2009).

Simulation models

Crop growth simulation models and biogeochemical and biophysical models have been very helpful in projecting the future crop and soil productivity. These models in connection with different GCM models predict the future agricultural practices that can adapt to different climate change scenarios. Here are a few of the models that can be used for different scenarios analysis to combat impact of climate change on agricultural production of the globe.

Simulation models that are able to assess climate change impact on crop growth, yield and farm economy, still lack complete feedback structures. Only single aspects can be investigated. However, modelling these single aspect increases knowledge on to the aspects of expectations from climate change, if interpreted carefully and in the context of the model’s abilities. Simulation models are widely used to address "what if" type questions, such as, what if the climate changes, different irrigation or fertilization regimes are used, different sowing dates are used, different cultivars are used, etc. In addressing actual yield predictions required by governments, private corporations, or NGOs, different types of simulation models are used for solving these "what if" type questions. Here, capabilities of different simulation models will be discussed in assessing the impact of climate change on agro ecosystem and what would be the possible mitigation and adaptation.

Agricultural Production Systems sIMulator (APSIM)

APSIM was developed to simulate biophysical processes in farming systems, particularly as it relates to the economic and ecological outcomes of management practices in the face of climate risk. APSIM is structured around plant, soil and management modules. These modules include a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls. APSIM resulted from a need for tools that can provide accurate predictions of crop production in relation to climate, genotype, soil and management factors, while addressing the long-term resource management issues.

Decision Support System for Agro-technology Transfer (DSSAT)

DSSAT is a software package integrating the effects of soil, crop phenotype, weather and management options that allows users to ask "what if" type questions and simulate results by conducting, in minutes on a desktop computer, experiments which would consume a significant part of an agronomist's career. It has been in use for more than 15 years by researchers in over 100
countries. The DSSAT simulates growth, development and yield of a crop growing on a uniform area of land under prescribed or simulated management as well as the changes in soil, water, carbon, and nitrogen that take place under the cropping system over time.

**Cropping Systems Simulation Model (Crop Syst)**

CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time step crop growth simulation model, developed with emphasis on a friendly user interface, and with a link to GIS software and a weather generator (Stockle, 1996). The link to economic and risk analysis models is under development. The model’s objective is to serve as an analytical tool to study the effect of cropping systems management on crop productivity and the environment. For this purpose, CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, crop canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and pesticide fate. These are affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation (including fallow years), cultivar selection, irrigation, nitrogen fertilization, pesticide applications, soil and irrigation water salinity, tillage operations (over 80 options), and residue management.

**INFOCROP**

InfoCrop, a generic crop model, which simulates the effects of weather, soils, agronomic management (planting, nitrogen, residues and irrigation) and major pests on crop growth, yield, soil carbon, nitrogen and water, and greenhouse gas emissions (figure 5). InfoCrop considers various processes such as, crop growth and development, soil water, nitrogen and carbon, and crop–pest interactions. Each process is described by a set of equations, in which the parameters vary depending upon the crop/ cultivar (Aggarwal et al. 2006).

These are all the small examples of models that can used for assessing the impact of climate change on crop productivity. There are many other models they can be used for similar purposes. The biogeochemical models like CENTURY, DNDC and RothC are used for carbon sequestration studies also. Are all the models suitable for climate change assessment? It is possible that the models those taking into account the effects of temperature, and CO\(_2\) concentration on photosynthesis and radiation use efficiency are suitable. Most of the crop simulation models accommodate these effects though not for the field crops. The model need to be robust and has the wider applicability to all geographical situations can be a good tool for climate change assessments.

**Simulation models in climate change research**

Several previous studies have used crop models to study the impact or sensitivity of climate change on agricultural production. The effects of climate change and elevated CO\(_2\) concentration on wheat production using APSIM model in Australia has been investigated by several studies. These include the assessment on individual effects of rising temperature and CO\(_2\) concentration ([CO\(_2\)]) and rainfall changes and the compound impacts of temperature, CO\(_2\) and rainfall changes, c) or multiple probabilistic climate change scenarios indicated that impact of climate change differed significantly between soil types and locations, and in the higher rainfall region of south-western Australia wheat yield will increase for all likely future climate scenarios. They reported that Higher [CO\(_2\)] increased yield especially at drier sites while higher temperatures had a positive effect in the cooler and wetter southern part of the region. The main difference between soil types was that heavier clay soils are most vulnerable to reduced rainfall while sandy soils were more vulnerable to higher temperatures. Higher temperatures could both increase and decrease protein concentrations. Wang et al., (2009) used the APSIM model to simulate the growth and water balance processes for a 117 year period of baseline, 2050 and 2070 climatic conditions. The results showed that wheat yield reduction caused by 1°C increase in temperature and 10%
decrease in rainfall could be compensated by a 266 ppm increase in [CO$_2$] assuming no interactions between the individual effects. Temperature increase had little impact on long-term average water balance, while [CO$_2$] increase reduced evapotranspiration and increased deep drainage. Length of the growing season of wheat decreased 22 days in 2050 and 35 days in 2070 conditions as a consequence of 2.3°C and 3.8°C increase in temperature respectively.

Using DSSAT, Jones and Thornton (2003) simulated the impact of climate change on maize production in Africa and Latin America and showed that there is 10% decrease in aggregate maize production by 2055. Alexandrov & Hoogenboom (2000) simulated the impact of climate variability for the major crops, including maize and winter wheat, and assessed possible adaptation measures for Bulgarian agriculture under an expected climate change. Four transient GCM (ECHAM4, HadCM2, CSIRO-Mk2b and GFDL-R15) had been used in this study for climate change scenario. These GCM models had been used in DSSAT crop model and projected the shorter vegetative and reproductive growing season for maize and winter wheat during the 21st century. Projected yield reductions for winter wheat varied between 0 and 7% during the 2020s and 2050s, and between 4 and 20% in the 2080s. DSSAT also showed that by shifting the sowing date, yield loss can be reduced under different GCM climate change scenarios in this study. DSSAT crop model is widely used in climate change research over the globe.

The CENTURY ecosystem model is used to investigate how land use and climate affect SOM and plant growth. Bhattacharyya et al has evaluated CENTURY model using two long-term fertilizer trials representing Indo-Gangetic plain (2007), humid and semi-arid sites from India (2010). He also modeled soil organic carbon stocks and changes in the Indo-Gangetic Plains and predicted that, there will be a 21% decrease in SOC stocks in the IGP from 1967 to 2030. Many authors have tested CENTURY model and estimated the carbon turn over in climate changing scenario.

InfoCrop provides integrated assessment of the effect of weather, variety, pests, and soil and management practices on crop growth and yield, as well as on soil nitrogen and organic carbon dynamics in aerobic as well as anaerobic conditions, and greenhouse gas emissions. The model considers the key processes related to crop growth, effects of water deficit, flooding, nitrogen management, temperature and frost stresses, crop-pest interactions, soil water and nitrogen balance and (soil) organic carbon dynamics. Its general structure relating to basic crop growth and yield is largely based on several earlier models, especially SUCROS series, and is written in Fortran Simulation Environment (FSE) programming language. Krishnan et al (2007) used info Crop to show Impact of elevated CO$_2$ and temperature on rice yield in eastern India for GDFL, GISS and UKMO scenarios and predicted changes of -9.02, -11.30 and -21.35% respectively. She also suggested that limitations on rice yield imposed by high CO2 and temperature can be mitigated, at least in part, by altering the sowing time and the selection of genotypes that possess higher fertility of spikelets at high temperatures. Like that, Hebbar et al (2008) for cotton; Srivastava et al (2010) for sorghum; Boomiraj et al (2010) for Indian Mustard used info crop for assessment of respective crop under different climate change scenario.

The climate change scenarios study

The Intergovernmental Panel on Climate Change (IPCC, 2001) reported that the average global surface temperature will increase by between 1.4 and 3°C above 1990 levels by 2100 for low emission scenarios and between 2.5 and 5.8°C for higher emission scenarios of greenhouse gases and aerosols in the atmosphere. Over the land regions of the Indian subcontinent, the projected (area-averaged) annual mean surface temperature rise by the end of 21st century has been estimated to range between 3.5 and 5.5°C depending upon the future trajectory of anthropogenic radiative forcing (Lal et al., 2001). The projected temperature increase has a large seasonal and spatial dependency over India. During the monsoon season, the temperature rise over south India is
projected to be less than 1.5 °C by 2050s while the increase in surface temperature is more pronounced over north, central and east India (>2 °C). Probable changes in precipitation, cloudiness and solar radiation under the climate changes scenarios were not taken into consideration in this analysis in view of the significant uncertainties associated with non-linear, abrupt and threshold rainfall events projected by GCMs over the Indian subcontinent.

Fig. 2. Effect of increase in surface temperature on soybean grain yield as simulated by the APSIM model.

Fig. 3. Probability distribution yield under climate change (elevated temperature in Bhopal)
Impact of increase in surface air temperature on soybean and wheat yield

The increased in surface air temperature has tremendous effect on soybean as observed in long-term simulation by the APSIM model. The results revealed that there was significant decrease in yield of soybean from the normal (base line followed) (Fig. 2). The base line yield for this study was the long-term simulated yield of 16 years under recommended management practices followed for soybean. The probability distribution of soybean yield, presented in Fig. 2, described the probability of obtaining a specific amount of grain yield under the increased temperature scenario. The Fig. 2 presented that there is 50% probability of obtaining <1 t ha\(^{-1}\) of soybean grain yield under climate change scenario as predicted by the model, whereas the probability of getting same amount of grain yield under normal condition is observed to be <10%. So, the increased surface temperature by 3 degree during soybean growing season decreased the yield significantly which
suggested that in future due to climate change the yield of soybean is going to decrease to the tune of about 30%. Similar observation was also recorded for wheat and it is presented in Fig. 3.

Mall et al. (1999) reported that the yields in soybean are found to decline almost identically for the climate change scenarios as inferred from all the three GCMs for the case when a doubling of CO$_2$ with respect to the present-day atmosphere occurs. The simulated decline in crop yield was from 12% (GFDL model climate) to 21% (UKMO model climate) under the doubled CO$_2$ climate change scenario. The total above ground biomass was most affected under the UKMO model-generated climate scenario under both the levels of CO$_2$ (Table 3).

Table 3. Some crop growth parameters of the soybean variety ‘Bragg’ as simulated by crop simulation model for two CO$_2$ levels and temperature increase projected in selected GCMs (values represent average of 13 selected locations in India)

<table>
<thead>
<tr>
<th>CO$_2$ level</th>
<th>Crop growth parameters</th>
<th>$T_{obs}$</th>
<th>GFDL</th>
<th>GISS</th>
<th>UKMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>Yield (kg/ha)</td>
<td>3950</td>
<td>-13%</td>
<td>-19%</td>
<td>-21%</td>
</tr>
<tr>
<td></td>
<td>Change in yield</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>Total above ground biomass</td>
<td>7300</td>
<td>6900</td>
<td>6750</td>
<td>6650</td>
</tr>
<tr>
<td></td>
<td>Change in above ground biomass</td>
<td>0%</td>
<td>-5%</td>
<td>-7%</td>
<td>-8%</td>
</tr>
<tr>
<td></td>
<td>Maturity duration (d)</td>
<td>109</td>
<td>111</td>
<td>113</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>Change in maturity duration</td>
<td>0%</td>
<td>1%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Double</td>
<td>Yield (kg/ha)</td>
<td>5400</td>
<td>4750</td>
<td>4450</td>
<td>4250</td>
</tr>
<tr>
<td></td>
<td>Change in yield</td>
<td>0%</td>
<td>-12%</td>
<td>-18%</td>
<td>-21%</td>
</tr>
<tr>
<td></td>
<td>Total above ground biomass</td>
<td>10000</td>
<td>9450</td>
<td>9200</td>
<td>9100</td>
</tr>
<tr>
<td></td>
<td>Change in above ground biomass</td>
<td>0%</td>
<td>-5%</td>
<td>-7%</td>
<td>-8%</td>
</tr>
<tr>
<td></td>
<td>Maturity duration (d)</td>
<td>109</td>
<td>111</td>
<td>113</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>Change in maturity duration</td>
<td>0%</td>
<td>1%</td>
<td>3%</td>
<td>4%</td>
</tr>
</tbody>
</table>

Table 4. Mean predicted change in soybean yield under the fixed temperature and CO$_2$ scenarios (Bhopal)

<table>
<thead>
<tr>
<th>CO$_2$ concentration (ppm)</th>
<th>Base</th>
<th>+2</th>
<th>+4</th>
<th>+5</th>
</tr>
</thead>
<tbody>
<tr>
<td>390</td>
<td>0%</td>
<td>-19%</td>
<td>-26%</td>
<td>-27%</td>
</tr>
<tr>
<td>450</td>
<td>+10%</td>
<td>-19%</td>
<td>-23%</td>
<td>-23%</td>
</tr>
<tr>
<td>550</td>
<td>+23%</td>
<td>-18%</td>
<td>-19%</td>
<td>-20%</td>
</tr>
<tr>
<td>650</td>
<td>+32%</td>
<td>-15%</td>
<td>-17%</td>
<td>-18%</td>
</tr>
</tbody>
</table>

Combined effect of CO$_2$ and temperature on soybean yield

Increase in CO$_2$ concentration increased the soybean yield whereas increase in temperature decreased soybean yield. The decrease was less when temperature in CO$_2$ in combination was used for simulation (Table 4).

Increasing temperature reduced mustard grain yield, while increase in CO$_2$ concentration increased crop yield. Increase in CO$_2$ from 369 to 550 ppm with no change in temperature has resulted in 15.8–31% increase in yield of irrigated mustard across different regions. Positive yield response of mustard to elevated carbon dioxide was due to, increased photosynthetic activity resulting in increased specific leaf area, leaf weight, biomass production and grain number. But the positive effect of increase in CO$_2$ concentration was nullified by temperature rise. Under irrigated condition, the grain yield dropped steeply with rise in temperature in eastern India. In this region, yield reduction was maximum (86.6%) with 5 °C rise in temperature. Rise in temperature coupled with rise in CO$_2$ to 450 and 550 ppm decreased yield reduction to 82.4 and 79.4% respectively. Yield reduction of mustard was moderate in northern part of the country (Fig. 4). In north India,
temperature rise by 5 °C, with no rise in CO2 reduced mustard yield by 34.7%. Rise in CO₂ along with temperature caused less yield reduction of mustard in this region. Mustard crop grown in central part of the country was also vulnerable to temperature rise, where substantial yield loss was observed. Temperature rise would be most harmful for the crop in eastern region, followed by central India, where winter season temperature is comparatively higher than northern region. Further rise in temperature in these locations would cause substantial yield reduction in this crop.

**Fig. 4.** Effect of CO₂ and temperature on simulated yield of irrigated and rainfed mustard in different locations in India.

**Conclusion**

Climate change is expected to influence crop production, hydrologic balances, input supplies and other components of agricultural systems. However, the nature of these biophysical effects and the human responses to them are complex and uncertain. Agricultural systems are also dynamic; producers and consumers are continuously responding to changes in crop yields, food prices, input prices, resource availability, and technological change. Accounting for these adaptations and adjustments is difficult but necessary in order to measure accurately climate change impacts. It is important to estimate crop yield (changes) by the use of crop biophysical simulation models that embed parameters drawn from crop experiments. Because climate change is likely to cut across a host of environmental factors, most quantitative estimates of climate change effects on crop yields are derived from such crop simulation models. While the use of crop simulation models makes tractable the assessment of climate effects across a range of crops, such
models also have limitations, including variability of factors and conditions that affect production in the field.

**Future research works**

- Development of regional climate change models by downscaling global climate projections for climate change research for a country.
- Development of a Geographical Information System (GIS) -based framework for assessing the risk of climate change for primary production systems in agriculture.
- Development of crop production systems with lower emissions of GHGs, that are sustainable, with respect to impacts on other environmental factors or attributes, and capacity to adapt to climate change.
- Research into methods to reduce nitrous oxide emissions from applied fertiliser.
- Research into methods to manage emissions from manure in intensive livestock industries.
- Research into use of bio-char and recycled organics as a soil amendment to sequester carbon, improve soil organic carbon, improve water holding capacity and nutrient cycling.
- Quantification of the impacts of management practices on soil carbon and parameterisation of models of soil carbon dynamics for agricultural and forest systems.
- Research into the interactive effects of increased atmospheric carbon dioxide in a water and nutrient limited environment on growth of major crop, pasture and forest species. Good understanding of the impacts of climate change will inform adaptation strategies.
- Research into the impacts of climate change on product quality, in all agricultural and forest systems, to inform breeding programs and development of adaptation strategies.
- Do plants acclimatize to changing temperatures? What plants are most vulnerable and where?

**Reference**


Robertson, M.J., Sakala, W., Benson, T., Shamudzarira, Z., 2005. Simulating response of maize to previous velvet bean (Mucuna pruriens) crop and nitrogen fertilizer in Malawi. Field Crops Res. 91, 91-105.

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Introduction

Globalization of agriculture has thrown up a new challenge to the agrarian sector. The descending trend in the global prices of agricultural commodities, especially food grains, endangers the sustainability and viability of the majority of farming communities, who are dependent for their food security through tiny pieces of lands (Joshi, 2003). Stagnating technological advancement and declining investment in agriculture had impeded to compete at the global level on many agricultural commodities. The threat is worsened by the inherent problems of widespread poverty and malnourishment acute rural unemployment and severe land degradation. Agricultural diversification in favor of more competitive and high-value enterprises is reckoned an important strategy to overcome the emerging challenges. In many developing countries, diversification has become an integral part of structural adjustments and transformation of agricultural sector. In the traditional subsistence system, agriculture is a coping mechanism for risk aversion. In the market-led environment, it is a strategy to allocate resources optimally, augment farm income, generate employment opportunities, alleviate poverty, conserve precious soil and water resources, and intensify export (Joshi et al., 2002).

Most of the developing countries are dependent on agriculture for their economic as well as industrial development. Agriculture is the backbone of the economy in India. Crop production can be increased by increasing the extents of agricultural land but reduction in land holdings has made it an impossible task. Another way to enhance crop production is to extent the land area by converting uncultivated land, adoption of innovative technologies, crop diversification etc. Technologies continue to be developed will have an impact on future crop production. In the future the potential for yield improvement will be through technological innovations. The crop production could be enhanced with the use of modern technologies like improved seed, fertilizer and crop protection chemicals.

Diversified agroecosystems became more important for agriculture due to increased climate fluctuations. Studies shown that crop yields are highly sensitive to changes in temperature and precipitation, especially during growth stages like flower and fruit development. Maximum and minimum temperatures along with seasonal shifts have large effects on crop growth and production. Variability of precipitation, flooding, drought, and more extreme rainfall events have affected food security in many parts of the world (Parry et al., 2005). Environmental changes also have affected many different aspects of agricultural production. Crop and ecosystem responses are getting affected with greater climate variability, shifting temperature, precipitation patterns, and other global change components which will affect integral agricultural processes. It results in changes in nutrient cycling, soil moisture, shifts in pest occurrences and plant diseases ultimately affect food production and food security (Fuhrer, 2003; Jones and Thornton, 2003). Thus, these changes have impact on abiotic and biotic stress, forcing agricultural systems to function under greater levels of perturbation in the future. Because of the impacts that climate change may have on agricultural production, the need to consider diversified agricultural systems is ever more pressing. Thus, crop diversification in context to resilient climate change has numerous challenges. Some important challenges are pest, disease and nutrient management Crop diversification strategies could help to meet out these challenges to feed the burgeoning population. Here attempt has been made to suit crop diversification for the changing scenario of climate change. Under such situation agriculture has to be strengthened from the unexpected incidences of insect and pests.
Thus agricultural production has to face several challenges in terms of shrinking land, increasing food demand, control of insect, pest and disease.

Agricultural Diversification

Agricultural diversification is slowly picking up momentum in favor of high-value food commodities primarily to augment income rather than the traditional concept of risk management. The nature of diversification differs across regions due to existence of wide heterogeneity in agro-climatic and socio-economic environments. It was considered interesting to delineate the key regions and sub-sectors of agriculture where diversification was catching up fast. Crops, livestock, fisheries and forestry constitute the core sectors of agriculture. The crop sector is the principal income-generating source in agriculture followed by the livestock sector. A strong synergy exists between these two sectors as they are complementary to each other. The fisheries sector has a prominence in the coastal areas and forestry dominates in the hilly regions.

Why Crop Diversification?

Crop diversification is intended to give a wider choice in the production of a variety of crops in a given area so as to expand production related activities on various crops and also to lessen risk. Crop diversification in India is generally viewed as a shift from traditionally grown less remunerative crops to more remunerative crops. The crop diversification (shift) also takes place due to governmental policies and thrust on some crops over a given time. For example, in India the Technology Mission on Oilseeds (TMO gave thrust on oilseeds production as a national need for the country's requirement to reduce imports. Market infrastructure development and certain other price related supports also induce crop shift. Often low volume high-value crops like spices also aid in crop diversification. Higher profitability and also the resilience/stability in production also induce crop diversification, for example sugar cane replacing rice and wheat. Crop diversification and also the growing of large number of crops are practiced in rainfed lands to reduce the risk factor of crop failures due to drought or less rain. Crop substitution and shift are also taking place in the areas with distinct soil problems. For example, the growing of rice in high water table areas replacing oilseeds, pulses and cotton; promotion of soybean in place of sorghum in medium and deep black soils (Vertisols) etc

What is Crop Diversification?

Crop diversification can be a useful means to increase crop output under different situations. Crop diversification can be approached in two ways. The main form and the commonly understood concept is the addition of more crops to the existing cropping system, which could be referred to as horizontal diversification. For instance, cultivation of field crops in rice fields or growing various types of other crops in uplands have been defined as crop diversification. The systems of multiple cropping have been able to increase food production potential to over 30 t/ha, with an increase of the cropping intensity by 400-500%. The other type of crop diversification is vertical crop diversification, in which various other downstream activities are undertaken. This could be illustrated by using any crop species, which could be refined to manufactured products, such as fruits, which are canned or manufactured into juices or syrups as the case may be. Vertical crop diversification will reflect the extent and stage of industrialization of the crop. It has to be noted that crop diversification takes into account the economic returns from different crops. This is very different to the concept of multiple cropping in which the cropping in a given piece of land in a given period is taken into account. Besides the above, some other terminologies are also used to define crop diversification. There are terms such as “crop substitution” and “crop adjustment”. It is necessary to indicate here that crop substitution and adjustment are linked to the main concept of crop diversification and are strategies often used to maximize profit of growing varieties of crops.

Concepts of Diversification
At the national level, diversification is concerned with the inter-sectoral transfer of resources, production, and income in an economy (agriculture, industry, services, etc.) Within the agriculture sector, diversification is a shift from one crop to another crop, or from one enterprise to another, in terms of area, production, income, uses, and transfer of resources (Joshi, 2003). It is an additional complementary of supplementary enterprise to the main enterprise, e.g., mixed crop livestock system. Thus, the nature of diversification can be classified as (Joshi, 2003):

1. A shift from farm to non-farm activities;
2. A shift from less profitable crops or enterprises;
3. Use of resources in diverse and complementary activities.

**Benefits of Diversification**

Micro-level studies on diversification showed that a shift towards high-value crops benefited the poor by directly generating employment and raising agricultural productivity. The producers who diversify their production as well as the hired laborers receive direct income benefits. Similarly, diversification in the rain fed and marginal environments is an insurance scheme that diffuses risk, arrests resource degradation, and reduces biotic and abiotic losses. Diversification of agriculture in favor of commercial crops leads to greater market orientation of farm production and progressive substitution of non-traded inputs in favor of purchased inputs (Joshi et al., 2002).

Now, the world is gradually diversifying with some inter-country variation in favor of high-value commodities (fruits, vegetables, livestock and fisheries). Agricultural diversification is strongly influenced by price policy, infrastructure development (especially markets and roads), urbanization and technological improvements. Rainfed areas are benefited more as a result of agricultural diversification in favor of high-value crops by substituting inferior coarse cereals. A sound and empirical understanding about nature of agricultural diversification and the constraints in accelerating its speed are needed. This would support in crafting appropriate policies for the evolution of required institutional arrangements and creation of adequate infrastructure development.

There are several advantages of crop diversification, namely (i) Comparatively high net return from crops (ii) Higher net returns per unit of labour (iii) Optimization of resource use (iv) Higher land utilization efficiency (v) Increased job opportunities. In order to achieve the above benefits the process of diversification should be changed from very simple forms of crop rotations, to intensive systems such as relay cropping and intercropping or specialization by diversifying into various crops, where the output and processing etc., could be different. This process could be similar at farm level and national level.

**Factors Affecting Crop Diversification**

Primary constraints for achieving food security are the low yield per unit area, high population pressure, and negligible scope for expansion of the area of land for cultivation. Under such situation available options will be crop intensification and diversification through the use of modern technologies, especially seeds, fertilizer, irrigation, mechanization of agricultural production, post-harvest processing, storage, marketing and development of new technologies by research.

**Crop Nutrition:**

Fertilizers and manures are major contributors to enhance yield and sustained production. The amount of fertilizers is generally lower in the developing countries than in developed countries. However, danger of overuse has not been a problem in the highly industrialized countries. Organic matter usage has been less in most countries. Its incorporation into the agricultural systems will make the soils fertile and less degradable. But use of organic manures has several constraints such as the volume required, time, labour and opportunity costs. Another recent
development is in the development of crop rotations, a strategy towards diversification of agricultural systems to increase productivity and crop yields. This involves the inclusion of green manure cover crops or other legumes in the cropping systems. The popular crop mixes are legumes in maize and other cereals. Along with fertilizers it is also necessary to encourage the use of organic manures to renovate soils and improve their physical and chemical properties and biological activity. Similarly, use of slow release organic fertilizers is also advisable to enhance nutrient use efficiency. Now-a-days nano fertilizers are under testing in the laboratory for their high efficiency at optimal low dose.

**Agricultural Mechanization:**

Farm power includes human, animal and mechanical sources. In developing countries 80 percent of the farm power comes from humans. There is a trend for the shift of labour from agriculture to industry in most of the developing countries. This has already taken place in the developed countries. It will also use appropriate farm machinery in the production chain to make farming more efficient and enable farmers to diversify cropping by growing more crops. In many countries mechanization of agriculture has led to improved yields and high labour productivity. It is reported that in China use of mechanization has led to 10% yield enhancement and 5% additional when irrigation was included. Thus, use of machinery for harvesting and processing increases yield by simply reducing crop losses. The post-harvest losses are reported as 20-40% in developing countries. Saving this amount is equal to increasing the yield without any added costs. Use of agricultural machinery shows an upward trend in our country.

**Irrigation:**

Water was considered a free resource in many countries. It has suddenly become a scarce commodity. Now it is treated as an agricultural input with a major threat to food production and food security. Irrigation is highly important to have efficient crop diversification. Water use efficiency could be enhanced with judicious use of water resources. The principle of micro-irrigation to deliver water to the root zone as the crop needs it, is no less valid for fertilizer. The combination of irrigation water with fertilizer, known as “fertigation” will be an obvious solution to get maximum benefits from their inputs while conserving the environment. Micro-irrigation will be an efficient tool to increase water use efficiency and its adoption is increasing. The micro-irrigated area has increased from 10,000 ha in 1975 to 104,000 ha in 1999 in Israel, reported Gunasena. Therefore, fertigation helps to economize both water and nutrient thereby conserve natural resources and protect the environment.

**Use of Improved Seed:**

Quality seed like certified seed, breeder’s seed, is important for optimum plant stand in the farmers’ field. Improved seed is one of the major contributors to crop diversification through development of appropriate cropping systems. The quality seed development at national level will be essential for yield improvement. The increase in annual yield of rice and wheat was attributed to use of improved seed coupled with better management practices. In India, estimated area planted to HYVs has increased from 62% in 1989 to 70% in 1999. Wheat has highest coverage under modern varieties among other cereals. It is estimated that more than 70% of the wheat acreage is under improved varieties in major wheat producing countries i.e. Bangladesh, China, India and Pakistan. In other crops, use of improved varieties is not extensive, but there is plenty of scope as farmers are quite responsive to the new varieties and have increasingly adopted them as and when they are released for cultivation.

**Protected Agriculture:**

The most recent addition to crop diversification is the introduction of crop production under controlled environments. Weather parameter like relative humidity, temperature, moisture level need to grow crops under controlled. Thus protected agriculture has made rapid headway and
became popular among middle income agriculturists. In these systems various factors of the environment such as air, temperature, humidity, atmospheric gas composition, nutrient factors etc., are controlled. These technological developments coupled with use of high quality crop varieties are integrated into a system of agricultural production, which is referred to as protected agriculture. The main forms of protected agriculture include the use of mulches, row covers and poly-tunnels. It has been a common practice to use organic mulches such as straw, dead leaves, coir dust etc., to modify the environment to make soil more favourable (weed and moisture control) for plant growth. Plastic mulches are also used for the production of high-value crops. Plastic mulches with drip irrigation are widely used as irrigation water and fertilizers (fertigation) helps in reducing cost of production. The use of polyester sheets over rows of plants help to prevent crop damage by insects, sunlight and sometimes frost in cooler areas. Now-a-days hydroponics and drip irrigation are the major areas of protected agriculture practiced in different countries. Thus, the high yields are achieved by practicing controlled environment agriculture. Similarly, the diversification into selection of high-value crops such as tomato, sweet corn, red, green and yellow bell peppers, strawberry, cauliflower, cucumbers, cantaloupe, lettuce, green peas and ornamentals/cut flowers those have markets both locally and overseas could be adopted. Thus these crops with high genetic potential for yield and quality will be essential for success of crop diversification.

**Organic Farming:**

Organic farming is the process of producing food naturally without the use of chemicals. This method avoids the use of synthetic chemical fertilizers and genetically modified organisms to influence the growth of crops. The main idea behind organic farming is ‘zero impact’ on the environment. The main aim of the organic farmer is to protect the earth’s resources and produce safe, healthy food. Organic farming includes all types of agricultural production systems, which are environmentally, socially, and economically sound. It is also different to traditional farming in that it involves a holistic approach to sustainable agriculture. This form of crop diversification has spread on the continent, particularly in Germany, Switzerland, Austria, Denmark, Sweden and Finland and is spreading into the Asian and African continents. The demand for organically grown food is gaining momentum all over the world.

**Role of Farming Community:**

The farmer participation is very important for successful in adoption and implementation of new technologies. It is also necessary to combine farmers’ traditional knowledge with the contribution of sciences. It strengthen the crop by taking into account their needs, values and objectives. Crop diversification strategies have failed in most cases due to ignorance of farmer involvement and external and internal factors that affect the system. One of the major issues is also crop selection. In rice-based crop diversification, crop selection does not pose a severe problem as it depends on the soil type. In upland crop diversification, crop selection and management depends on market values and past experience. A sustainable programme of diversification could be achieved only through farmer participation in the planning process. Under changing scenario of climate, farmers’ needs strategic and contingency crop planning. Under such situation, they prefer to go for short duration and low input responsive crop cultivars.

**New Technology Development:**

Modern biotechnology in which characteristics based on single genes can be transferred from any organism to plants has resulted in transgenic plants combining disease or insect or herbicide tolerance. Therefore, the emerging genetic technologies could be beneficial to farmers due to their cost effectiveness. However, use of transgenic crops has come under severe scrutiny in recent times and some countries have completely banned their import until the actual situation is clarified. It is now widely acknowledged that conventional technologies will be less than adequate
to double food production, and biotechnology will be an essential strategy to achieve food security in India.

Climate Change and its Impact on Crop Production

Diversified agroecosystems have become more important for agriculture as climate fluctuations have increased. Research has shown that crop yields are quite sensitive to changes in temperature and precipitation, especially during flower and fruit development stages. Temperature maximums and minimums, as well as seasonal shifts, can have large effects on crop growth and production. Greater variability of precipitation, including flooding, drought, and more extreme rainfall events, has affected food security in many parts of the world (Parry et al. 2005).

Agricultural vulnerabilities have been found in a number of important crop species. (i) Rice: Observations of rice production in the Philippines during an El Niño drought season showed reductions in seed weight and overall production (Lansigan et al. 2000). (ii) Wheat: Studies of wheat have demonstrated that heat pulses applied to wheat during anthesis reduced both grain number and weight, highlighting the effect of temperature on spikes grain fill (Wollenweber et al., 2003) (iii) Maize: In maize, researchers observed reduced pollen viability at temperatures above 36°C, a threshold similar to those in a number of other crops (Porter and Semenov, 2005). Such observed agricultural vulnerabilities to changes in temperature and precipitation point to the need to develop resilient systems that can buffer crops against climate variability and extreme climate events, especially during highly important development periods such as anthesis. There are a variety of ways that diversified agricultural systems exemplify that more structurally complex systems are able to mitigate the effects of climate change on crop production.

Impact on rice-wheat system of IGP

The effect of climatic changes on productivity and production in a rice-wheat system is generally accepted. What has not received sufficient attention is the effect of the rice wheat system on local and global climate changes. A shift to, or intensification of, rice-wheat systems in the Indo-Gangetic Plains has resulted in seasonal wet and dry crop cycles, a heavy reliance on irrigation and an increased fertilizer usage accompanied by indiscriminate burning of crop residues. The emission of greenhouse gasses CO₂, CH₄ and N₂O in rice-wheat systems and other environmental concerns associated with foodgrain production now beg for attention.

For instance, an increase of temperature by 1°C in the Indo-Gangetic Plains would be equivalent to a 150 km Northward shift of isotherms (lines joining places with similar temperature) or about 150 m lower altitude. There is a 5% decrease in rice yield for every °C rise above 32°C

Inter-relationship of CO₂, Temperature and Yields

Long-term experiments in the region have shown that degradation of soil fertility has led to decline in yields of rice and stagnation in wheat production. In particular, soil organic matter decline has been of importance because it impacts on both soil fertility and soil structural stability. However, soil organic matter decline seems inevitable given the farmers’ practices of burning virtually all crop residues and manure generated by livestock, fed thereon. Decline in soil structure compounds yield decline due to nutrient deficiencies. Addition of 15 t/ha/annum of organic inputs (farmyard and green manure) in conjunction with NPK fertilizers consistently increased yields of wheat compared to NPK fertilizers alone in a 39 year experiment, but rice yields declined regardless (Wanjari and Singh, 2010). The role of tillage under warm, wet conditions in fostering rapid soil organic matter loss and the consequence for CO₂ emissions into the atmosphere also needs to be taken into account.

Higher atmospheric CO₂ content increases grain yields. However, wheat yields are unlikely to increase by more than 10% for double pre-industrial CO₂ levels] even under optimal field conditions, because of decrease crop duration (and hence yield) as a consequence of warming. A
5% to 7% increase in wheat yields in more likely under average management conditions. The prognosis for rice is even worse. Spikelet sterility is caused when temperature exceeds 32°C at flowering. There is a reduction in yield of about 5% per °C rise above 32°C. This is unaffected by, and may even offset the benefits of, an elevated CO₂ level.

**Sources of GHG**

Agriculture is said to be one of the sources of green house gases (GHG). Unfortunately, contribution to GHG is actively from rice-wheat system, a most prevalent system of Indo-gangetic Plains. Rice-wheat systems produce greenhouse gases through both biological processes and burning of fuel by farm machinery. It has been illustrated one by one as follows:

**Carbon Dioxide**

Tillage operations contribute CO₂ through the rapid organic matter decomposition due to exposure of larger surface area to increased oxygen supply. Experiments in Mexico have shown that tillage almost doubles the rate of decline in soil organic carbon levels in the top 20 cm of soil. Every liter of diesel fuel used by tillage machinery and irrigation pumps also contributes 2.6 kg CO₂ to the atmosphere. Thus, nearly 400 kg CO₂ would be generated per hectare assuming an annual use of 150 liters diesel in the conventional rice-wheat system. For the 12 million ha, this would amount to 4.8 Mt CO₂ per annum or 1.3 MMTCE. This is one third the value (4 MMTCE) of CH₄ from recefields. Diesel use remains greatly an underestimated source of GHG.

The presence of nitrogen (N) enhances microbial decomposition and release of CO₂ is production of N fertilizers. For ever Kilogram of N fixed in fertilizer 1.8 kg CO₂ is the by-product. It is presumed that CO₂ generated by burning crop residues will be taken up by the following crop.

**Methane**

Methane is produced by fermentation, i.e., anaerobic decomposition of organic matter reducing CO₂ to CH₄. The continuously flooded rice fields produce CH₄ due to their anoxic conditions and rice plants serve as conduit for its release to atmosphere. Multi-localational experiments in five countries studied CH₄ emission rates that also showed seasonal variations. Rainfed rice showed less than half of the emission from irrigated fields. The CH₄ emission rate can be greatly reduced single or multitude aeration of fields instead of continuous flooding. In 12 million ha of rice-wheat in the Indo-Gangetic Plains about 0.7 Mt of CH₄ per year (or 4 MMTCE/annum) is produced by rice cultivation. This is primarily due to low organic carbon levels in this region.

The burning of crop residues contributes about 0.14 Mt of CH₄ (0.8 MMTCE/annum) assuming that half of the crop residues produced at the rate of 10 t/ha (rice and wheat) in the 12 million ha are burnt. This is equivalent to 20% of the total CH₄ emitted from paddy fields in the same area.

**Nitrous Oxide**

This gas is released even from soils to which no nitrogen containing fertilizer has been applied. Destruction of the ozone layer due to N₂O is an important consideration beyond the concern for nitrogen losses from applied fertilizers and manures. Experiments have shown that both the processes of nitrification and denitrification contribute to the release of N₂O from the soils into atmosphere.

The N₂O production is greatly affected by soil water content. Water creates anaerobic conditions by slowing down the diffusion rate of oxygen by ten thousand times. Generally, an increase in denitrification and potential N₂O losses is observed following irrigation or rain in aerobic or partially aerobic soils. Rice paddies are not considered to be an important source of atmospheric N₂O because it is further reduced to N₂ under strong anaerobic conditions due to standing water. N₂O flux increases sharply due to draining of the fields at mid-tillering stage.
The burning of crop residue produces 40 g N₂O/t. assuming as before that half of the 10 t/ha crop residue produced on 12 million ha is burnt, then 2000 tons of N₂O (about 0.2 MMTCE/annum) is released into the atmosphere. This is almost a quarter of the value derived in terms of CH₄ from the same process.

**Crop Diversification Strategies for Climate Change**

The climate change will affect both (i) biotic (pest, pathogens) and (ii) abiotic (solar radiation, water, temperature) factors in crop systems, threatening crop sustainability and production. More diverse agroecosystems with a broader range of traits and functions will be better able to perform under changing environmental conditions (Matson *et al.*, 1997; Altieri, 1999), which is important given the expected changes to biotic and abiotic conditions. The following are a few of the major ways that the greater functional capacity of diverse agroecosystems has been found to protect crop productivity against environmental change.

**Date of Sowing:**

Studying the effect of weather variability on field crops through different date of sowing is considered as a simplest technique to predict the probable crop responses to the climate change/variability (Bhatt *et al.*, 2012). It will be helpful to make contingency planning to fit proper variety to extreme weather conditions like raising and decreasing temperatures, varying rainfall and other weather components. Thus, best performing crop variety will be screened through crop variety trial. The suitable variety would be adopted on large scale on farmers’ field by testing these crop varieties on farmer’s fields.

**Crop Rotation:**

Increasing diversification of cereal cropping systems by alternating crops, such as oilseed, pulse, and forage crops, is another option for managing plant disease risk (Krupinsky *et al.*, 2002). Disease cycles could be interrupted through crop rotation by interchanging cereal crops with broadleaf crops that are not susceptible to the same diseases. Although changes in disease spread and severity are uncertain under climate change, greater genetic variation across space and time could potentially reduce adverse disease transmission impacts that may accompany climate change. It is well documented that continuous monocropping (rice-wheat) for longer periods with low system diversity (Dwivedi, 2003). It resulted in loss of soil fertility due to emergence of nutrient deficiencies, deterioration of soil physical properties decline in factor productivity and crop yields in high productivity areas (Saha *et al.*, 2012). Introduction of legume crop in rice-wheat cropping system helps in addition of nitrogen, nutrient recycling from deeper soil layers, minimizing soil compaction, increase in soil organic matter, breaking of weed and pest cycles and minimizing harmful allelopathic effect (Saha *et al.*, 2012).

**Reduced Tillage:**

Reduced tillage could enhance soil biodiversity thereby leading to greater disease suppression. It helps to establish crop stand so that densities could be adjusted to allow for better microclimatic adjustments to disease growth. These examples show that farmers can take advantage of greater crop diversification to reduce disease susceptibility in agricultural systems, thereby limiting the amount of production loss as a result of crop diseases.

**Pest Management:**

Pest management is a perennial challenge to farmers, and it is a very important ecosystem service. In agricultural systems, as in natural ecosystems, herbivorous insects can have significant impacts on plant productivity. The challenges of pest suppression may intensify in the future as changes in climate affect pest ranges and potentially bring new pests into agricultural systems. It is expected that insect pests will generally become more abundant as temperatures rise as a result of range extensions and phonological changes. This abundance will be accompanied by higher rates of population development, growth, migration, and overwintering (Cannon, 1998, Bale *et al.*, 2002).
Farmers may be able to assist in creating biotic barriers against new pests by increasing the plant diversity of their farms in ways that promote natural enemy abundance. Crop diversity is critical not only in terms of production but also because it is an important determinant of the total biodiversity in the system (Matson et al., 1997). With greater plant species richness and diversity in spatial and temporal distribution of crops, diversified agroecosystems mimic more natural systems and are therefore able to maintain a greater diversity of animal species, many of which are natural enemies of crop pests (Altieri, 1999). Many examples of pest suppression have been shown within agricultural systems possessing diversity and complexity, especially in comparison with less-complex systems (Cannon, 1998).

**Disease Management:**
Losses caused by pathogens can contribute significantly to decline in crop production. Climate changes potentially could affect plant disease distribution and viability in new agricultural regions. The effect of climate change on disease prevalence is therefore much less certain. Climate change could have positive, negative, or no impact on individual plant diseases (Chakraborty et al., 2000). However, it is suspected that milder winters may favor many crop diseases, such as powdery mildew, brown leaf rust, and strip rust, whereas warmer summers may provide optimal conditions for other diseases, such as cercosporea leaf spot disease (Patterson et al., 1999). The loss of genetic diversity in crop production has led to a hypothesized increase in crop disease susceptibility as a result of higher rates of disease transmission. Many mechanisms reduce the spread of disease in agricultural systems with greater varietal and species richness. Barrier and frequency effects occur when other disease-resistant varieties or species block the ability of a disease or virus to transmit and infect a susceptible host (Finckh et al., 2000). Multiline cultivars and varietal mixtures have been used to effectively retard the spread and evolution of fungal pathogens in small grains and to control some plant viruses (Matson et al. 1997). One well-known example of barrier effects in rice production showed that genetic variation within species and within populations can increase the ability of an agricultural system to respond to pathogen diseases. It has also been demonstrated that in-field genetic crop heterogeneity suppresses disease in rice crops suffering from rice blast (Zhu et al., 2000). For instance, disease-susceptible rice varieties, when planted in mixtures with resistant varieties over large tracts of land, had 89% greater yield and 94% reduced fungal blast occurrence than when planted in monoculture. Because of this experiment’s success, fungicidal sprays were no longer applied to these fields after the trial. Rather, farmers grew rice in mixtures in order to improve the resilience of the systems while reducing economic costs.

**Habitat Management:**
It is one method used within agricultural systems to alter habitats to improve the availability of the resources natural enemies require for optimal performance (Landis et al. 2000). Such management techniques have been developed for use at within-crop, within-farm, or landscape scales, and some have been proven to be very economical for farmers. Gurr et al. (2003). Studies found that many degrees of complexity exist in increasing biodiversity for pest management. Simply diversifying the plant age structure of a monoculture or strip-cutting fields such that natural enemies have a temporal refuge can improve in-field habitats for natural enemies. Larger-scale changes, such as integrating annual and perennial noncrop vegetation; increasing crop diversity within the field; or increasing farmwide diversification with silviculture, agroforestry, and livestock may also provide a variety of other functions to the system (Gurr et al., 2003). The diversity of plant species within the agroecosystem therefore provides long-term pest suppression for agricultural systems by building up a bank of potential natural enemies for any future pest outbreaks in the system.
**Agroforestry Systems:**

To grow agricultural crops with forest trees and other agroforestry system is one of the strategies of crop diversification to combat climate change. Agroforestry systems also protect crops from extreme storm events (e.g., hurricanes, tropical storms) in which high rainfall intensity and hurricane winds can cause landslides, flooding, and premature fruit drop from crop plants. In a comparative study of farming systems in Sweden and Tanzania, two locations where agriculture has suffered from climate variation and extreme events, it was found that agricultural diversity increased the resilience of the production systems. Sweden suffered from cold-tolerance issues, whereas Tanzania suffered from problems of heat tolerance and irregular El Niño cycles. Both locations experienced greater seasonal drought. In these cases, incorporating wild varieties into the agricultural system and increasing the temporal and spatial diversity of crops has been found as the successful management practice (Tengö and Belfrage, 2004). Diversification of agricultural systems can significantly reduce the vulnerability of production systems to greater climate variability and extreme events, thus protecting rural farmers and agricultural production.

**Reducing Greenhouse Gases**

Positive changes in agronomic practices like tillage, manuring and irrigation can help reduce greatly the release of greenhouse gases into the atmosphere. Adoption of zero tillage and controlled irrigation can drastically reduce the evolution of CO$_2$ and N$_2$O. Reduction in burning of crop residues reduces the generation of CO$_2$, N$_2$O and CH$_4$ to a significant extent. Saving on diesel by reduced tillage and judicious use of water pumps can have a major role to play. Changing to zero tillage would save 98 liter diesel per hectare. With each liter of diesel generating 2.6 kg, about 3.2 Mt. CO$_2$/ ammonium (about 0.8 MMTCE) can be reduced by zero – tillage in the 12 million ha under rice- wheat systems in the Indo-Gangetic Plains alone. Intermittent irrigation and drainage will further reduce CH4 emission from rice paddies by 28% to 30% per the findings at IARI (Delhi) and at Pantnagar.

Use of calcium nitrate or Urea instead of ammonium sulphate and deep placement instead of surface application of nitrogenous fertilizers can increase its efficiency and plant uptake there by reducing N$_2$O emission.

**Crop Diversification Index**

The crop diversification indicates raising the variety of crops on arable land. It can be examined over space and time. This is based on agroclimatic, irrigation as well as technological consideration. Crop diversification index method seeks to identify the behavior of crops over a period and the space. It is one of the most important criteria of agricultural regionalization and useful for the identification of cropping pattern of the region. The main advantage of the study of diversification region lies in the fact that it enables us to understand the impact of physical and socio-economic conditions on the agriculture. Moreover, it helps us in knowing the contemporary competition among crop for area, for rotation and effect on double cropping, total production and per hectare productivity. Crop diversification patterns have great relevance like that of crop concentration, in agricultural land use studies. Crop diversity is an important component of cropping pattern of a region.

Larger the number of crops grown in an area during the year with each crop occupying equal proportion of crop land, the higher is crop diversification, specialization is reverse of diversification. Specialization indicates cultivation of a few number of crops, whereas crop diversification implies raising the variety of crops from the soil. “The keener the competition, the higher the magnitude of the diversification and lesser the competition the greater will the trend toward specialization or monoculture farming where emphasis is on one or two crops” (Jasbir Singh and Dhillon 2002). The modified formula developed is as follows:
Crop Diversification

\[
\text{Index (CDI)} = \frac{\text{Percentage of total harvested area under ‘n’ crops}}{\text{Number of ‘n’ crop}}
\]

The ‘n’ crops are those crops which occupy individually 5% or more of the harvested area. At present crop diversification is very high in tropical and subtropical countries of the world. The variation in spatial pattern of indices could studying the variation in indices four diversification levels are registered namely i) area of high diversification below 20, ii) area of moderate diversification 20 to 25, iii) area of low diversification 25 to 30 and, iv) area of very low diversification above 30. The crop diversification is inversely related i.e. lower the index more the diversification of crops and higher the index more the specializations, under agriculturally favorable condition such as suitable weather, fertile soil, mechanization availability of irrigation facilities the crop diversification is more while crop diversification decrease in the region unfavorable condition.

**Conclusion**

Emission of green house gases (GHG) either from agro-ecosystem or anthropogenic activities leads to global warming and climate change. These GHGs enact the changes depending on their global warming potential. From such climate changes, we are experiencing the erratic precipitation, shifting of monsoon onset & withdrawal, unexpected torrential rain and cyclone which have been some of the most immediate consequences. The climatic changes expected to influence abiotic and biotic stress. Such changes may have tremendous impact on agricultural production, thus the need to consider crop diversity is ever more pressing. The climate change may adversely affect crop production system due to non suitability of existing crop variety, water scarcity, insect and pest infestation. Therefore, crop diversification strategies would be based on date of sowing, crop rotation, reduced tillage, pest & disease suppression, habitat management, agroforestry etc. These strategies will be functional only when crop diversification followed in context to total biodiversity to effectively retard the spread and evolution of pest and diseases by growing multiline cultivars and suitable varietal mixtures.

**References**


3. Elevated Atmospheric CO₂ - Its Indirect Effects on Soil Processes

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Introduction

In recent decades, human induced changes in climate of the earth have the focus of scientific and social attention. The most imminent of this is increased concentration of Greenhouse Gases (GHGs) namely, carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) in the atmosphere. The Concentration of CO₂, CH₄ and N₂O have increased markedly by 30%, 145% and 15%, respectively as a result of human activity since the industrial revolutions (1750) (IPCC, 2007). The CO₂, CH₄ and N₂O concentration in the atmosphere were 280 ppm, 715 ppb and 270 ppb in 1750 AD. In 2005, these values have become 379 ppm, 1774 ppb and 319 ppb, respectively (IPCC, 2007). The increase in concentration of these gases in the atmosphere was higher in recent years i.e. 70% increase of GHGs between 1970 and 2004 has been reported. The global increase in CO₂ concentration are primarily due to consumption of fossil fuel and land use change, while those of CH₄ and N₂O are primarily due to agriculture.

Increase in concentration of the GHGs particularly CO₂ in the atmosphere is leading to global warming. Over the last 100 years (1906-2005) global mean surface temperature have increased in the order by 0.74 °C ± 0.18 °C. The rate of increase in temperature is highest in recent decades. Fourteen of the last seventeen years (1995-2011) rank the warmest years since 1850. IPCC has projected that by the end of the 21st century the temperature increase is likely to be in the range of 2 to 4.5 °C. The temperature rise is likely to be higher in winter (rabi) season than rainy (kharif) season. For South Asia region including India a rise in temperature of 0.88 °C to 3.16 °C by 2050 and 1.5 °C to 5.44 °C by 2080 has been projected by IPCC. Increase in temperature causes decline in glaciers and snow covers in Himalayas and increases in sea levels. The projected sea level rise by the end of this century is likely to be 0.18 to 0.59 m and may results in submergence of many coastal land areas. Climate change induces the change in earth’s atmospheric weather events like precipitation, air circulation, cyclonic storms and wind speed and direction. Precipitation is likely to increase by 15-40% by the end of this century. Together these effects alter the hydrological cycle and partitioning of carbon (C) between the atmosphere and the land surface. All of these can have a tremendous impact on vegetation, soil process, nutrient dynamics and soil health.

Elevated atmospheric CO₂ induced temperature and precipitation changes, directly or indirectly influences the major key soil processes which will subject the soils to physical and chemical degradation. A proper understanding is required, in order to better predict the likely impact of elevated atmospheric CO₂ on soil. The objective of this article is to assess the impact of elevated atmospheric CO₂ on various key soil processes.

Soil as a Source and Sink of Greenhouse Gases

IPCC concluded that the world wide agriculture accounts about 13.5% of global GHGs emission (Cline, 2007). Agricultural soil management is considered as a chief contributor to GHGs emission. Soil is one of the important sources and sinks for GHGs. It contributes about 20% to the total emission of CO₂ through soil respiration and root respiration, 12% of CH₄ and 60% of anthropogenic N₂O emissions (IPCC, 1996). Conversion of forests and grasslands to agriculture use substantially increased the atmospheric CO₂ concentration in past centuries. Global deforestation during 1850-1985 contributed approximately 120 Gt to the atmosphere (Cole et al., 1996), majority of the soil C losses occurs with in first few years, particularly in the tropics (Paustian et
al., 1997a, b). Application of higher doses of N fertilizers and microbial process like nitrification and denitrification in the soil increases the emission of N\textsubscript{2}O (IPCC, 1996). Production and emission of N\textsubscript{2}O from the soil to the atmosphere, accounts for about 70% of both anthropogenic N\textsubscript{2}O and natural N\textsubscript{2}O sources (IPCC, 1995). Soil production of CH\textsubscript{4} is associated with wetlands, flooded rice production, termites, landfills, and areas of oil and natural gas production, and about 40% of the roughly 500 Tg of CH\textsubscript{4} produced annually is produced in the soil. Natural wetlands occupy approximately 500–600 Mha and emit about 100 Tg of CH\textsubscript{4} annually (Matthews 1993). Flooded rice fields occupy about 148 Mha and emit about 50 Tg of CH\textsubscript{4} annually (Cole et al., 1996). The consumption of atmospheric CO\textsubscript{2} occurs mainly through carbon sequestration; improved crop production increased the residue return and better nutrient management increase C input in soil (Cole et al., 1996). In case of CH\textsubscript{4}, methane oxidizing bacteria in the soil consumes and converts it into CO\textsubscript{2} which further leads to acceleration of global climate change. Soil CH\textsubscript{4} consumption is influenced by agricultural practices and intensification of land use in both temperate (Bronson and Mosier, 1993) and tropical soils (Murdzyarso et al., 1996). The soil–atmosphere exchange of trace gases and relationship to global annual atmospheric budgets are explained in table 1. The anthropogenic induced input-output imbalance in the production system causes agricultural soils as a major contributor to the global warming.

Table 1. Soil-atmosphere exchange of trace gases and relationship to global annual atmospheric budgets

<table>
<thead>
<tr>
<th>Trace gases</th>
<th>Estimated soil emission</th>
<th>Total global emission</th>
<th>to the atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2}–C</td>
<td>70 Gt\textsuperscript{a}</td>
<td>160 Gt\textsuperscript{a}</td>
<td></td>
</tr>
<tr>
<td>CH\textsubscript{4}–C</td>
<td>110 Tg\textsuperscript{a}</td>
<td>400 Tg\textsuperscript{a}</td>
<td></td>
</tr>
<tr>
<td>N\textsubscript{2}O–N</td>
<td>10 Tg\textsuperscript{b}</td>
<td>15 Tg\textsuperscript{a}</td>
<td></td>
</tr>
</tbody>
</table>

Estimated soil consumption

<table>
<thead>
<tr>
<th>Trace gases</th>
<th>Estimated soil consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2}–C</td>
<td>0.5 Tg\textsuperscript{c}</td>
</tr>
<tr>
<td>CH\textsubscript{4}–C</td>
<td>30 Tg\textsuperscript{a}</td>
</tr>
</tbody>
</table>

\textsuperscript{a}IPCC (1995); \textsuperscript{b}Matthews (1993); \textsuperscript{c}Cole et al. (1996)

Contribution of Indian Agriculture To Global Warming

Indian agriculture is low input based and greatly challenged. India feeds 17% of global population in only 2.3% land area supported by 4% of fresh water resources. The cosmic rate of population increase may demand more from these limited resources in future and we have to adopt highly intensive agriculture which demands higher doses of fertilizers. It may further exploit the soil/land resources by depletion of soil organic carbon, secondary and micronutrients, and also enhance the greenhouse gases emission and the ground water contamination. So these conditions may lead agriculture as largely becoming a non-point source of environmental pollution. CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O are accounts for contributing 75%, 15% and 5% of GHGs, respectively (IPCC, 2007). Agriculture and allied sector produce about 35%, 50% and 70% respectively, of the total anthropogenic emission of these gases. In India out of total GHG emission from the anthropogenic activity, agriculture sector contributes 28%. The emissions are mainly due to clearance of forests for agricultural use which increases the emission of CO\textsubscript{2}, methane emission from rice fields (23%) and enteric fermentation in ruminant animals (59%), and N\textsubscript{2}O from application of manures and fertilizers (Fig. 1A and 1B) (NATCOM, 2004; Agarwal and Pathak, 2009). Bhatia et al. 2004 recently estimated for the base year 1994-95 that CH\textsubscript{4} and N\textsubscript{2}O emissions from Indian agricultural fields were 2.9 Tg (61 Tg CO\textsubscript{2} equivalent) and 0.08 Tg (39 Tg CO\textsubscript{2} equivalent), respectively.
Climate change is becoming a reality and it causes drastic changes in atmospheric CO$_2$ concentration and atmospheric temperature in recent decades. IPCC has predicted that by the end of the 21st century, the average temperature increase is likely to be 2°C. In addition to temperature changes, there are also changes in atmospheric moisture, precipitation patterns (frequency and intensity), frequency of drought and other weather extremes. All of these changes together may affect the soil and water resources of the world. Elevated atmospheric CO$_2$ has direct as well as indirect impacts on soil processes and properties through imposed changes in soil temperature, soil water and nutrient competition.

In general, soil processes are broadly classified into structural (physical) and hydrological processes, and biogeochemical processes. These processes are often working simultaneously in the soil and involved in influencing various soil quality parameters in any soil ecosystem. The structural and hydrological processes include aggregation-dispersion, removal of topsoil (erosion) and runoff, soil water availability and distribution and its movement. These processes mainly affect the soil structure, soil water and aeration and other related properties. Important chemical and biogeochemical processes that occur in the soil include mineralization-immobilization, dissolution-precipitation, sorption-desorption, and oxidation-reduction (Sanyal and Majumdar, 2009). They are involved in influencing dynamics of several nutrients, soil carbon dynamics, and ultimately soil biodiversity by creating competition in nutrient cycling. The key soil processes like soil forming processes, biogeochemical and hydrological processes are likely to be influenced by global changes. All these processes are temperature and moisture dependent and involve microbial mediated processes. Thus, elevated atmospheric CO$_2$ induced temperature and precipitation changes result in changes of these key soil processes which will subject the soils to physical and chemical degradation, soil erosion, salinization, decreased water availability, and changes in C and N dynamics, decreased nutrient storage in soil, and depletion of soil biodiversity. These unfavourable changes pose a big threat to soil productivity, soil and water quality, and sustainability of the production system (Emmett et al., 2009; Benbi and Kaur, 2009). The potential impacts of elevated atmospheric CO$_2$ on soil processes and resultant unfavourable changes in soil quality parameters are schematically summarized in Fig. 2. and briefly in the following discussions.
Fig. 2. The potential consequences elevated atmospheric CO$_2$ of on soil processes

Soil formation processes

Factors which affect the soil formation are climate, vegetation, parent material, topography and time. Among this climate and vegetation considered as active factors. Changing global atmospheric CO$_2$ may affect the climate particularly temperature and rainfall, and vegetation in an ecosystem. These changes accelerate the soil forming process by modifying the processes of chemical, biochemical or mineralogical changes in soil parent material over a period of time at prevailing topographic conditions.

The most rapid processes of chemical or mineralogical change under changing climatic conditions would be loss of salts and nutrient cations by leaching, and salinization. The clay mineral composition and the mineralogy of the coarser fractions would generally change little, even over centuries. Exceptions would be the transformation of X-ray amorphous material into the clay mineral halloysite when a volcanic soil previously under perennially moist conditions becomes subject to periodic drying, or the gradual dehydration of goethite to hematite in soils subject to higher temperatures or severe drying, or both. Changes in the surface properties of the clay fraction, while generally slower than salt movement, can take place much faster than changes in bulk composition or crystal structure. The effect of four potential scenarios on textural differentiation in soil profile is depicted in Fig. 3 (Brinkman & Brammer, 1990). Such surface changes have a dominant influence on soil physical and chemical properties (Brinkman, 1990).
Changes in the clay mineral surfaces or the bulk composition of the clay fraction of soils are brought about by a small number of transformation processes, listed below (Brinkman, 1982). Each of these processes can be accelerated or inhibited by changes in external conditions due to global atmospheric CO$_2$ change.

- Hydrolysis by water containing carbon dioxide, which removes silica and basic cations;
- Cheluviation, which dissolves and removes especially aluminium and iron by chelating organic acids;
- Ferrolysis, a cyclic process of clay transformation and dissolution mediated by alternating iron reduction and oxidation, which decreases the cation exchange capacity by aluminium interlayering in swelling clay minerals;
- Dissolution of clay minerals by strong mineral acids, producing acid aluminium salts and amorphous silica;
- Reverse weathering, i.e., clay formation and transformation under neutral to strongly alkaline conditions, which may create, e.g., montmorillonite, palygorskite or analcime.

Hydrolysis and cheluviation may be accelerated by increased leaching rates. Ferrolysis may occur where soils are subject to reduction and leaching in alternation with oxidation: in a warmer world, this may happen over larger areas than at present, especially in high latitudes and in monsoon climates. Dissolution by strong acids would occur, e.g., where sulphidic materials in coastal plains are oxidized with an improvement of drainage; however, a rise in sea level would reduce the likelihood of this occurring naturally. Reverse weathering could begin in areas drying out during global warming, and would continue in most presently arid areas. These processes would influence the surface properties of the clay fraction only over a period of centuries, even with the changes envisaged as a consequence of global warming.

Not only can the speed of soil formations be accelerated by human action, but also its very nature or direction. In most places, the natural soil-forming processes are not fundamentally changed, but there are certain threshold situations, generally with fragile soils, where even a small change in external conditions may cause a major, and adverse, change from one dominant soil-forming process to another. The four examples summarized below (from Sombroek, 1990) illustrate a change from hydrolysis to cheluviation (Ferralsols to Podzols); irreversible hardening
of the subsoil; clay illuviation forming dense subsoil in originally homogeneous, porous Ferralsols; and salinization. These changes in long run may alter soil formation processes in different degree as per the local environmental conditions prevailing in particular region cause the change in world soil distribution scenario.

**Soil organic matter dynamics**

Soil organic matter is elixir of life particularly to soil life. It acts as reservoir of soil nutrients which is become available to plant by mineralization processes. It is the food for many microbes which are living in the soil. It acts as both source and sink of atmospheric CO$_2$. Soil contains large amount of carbon compared to atmosphere and mostly in the organic form. Human activities particularly clearing of forests, intense farming practices mediated release of CO$_2$ tilting the input-output balance considered as source. Application of large amount of organic residues to the soil through enhanced biomass production from forests, incorporation of crop residues, exogenous application of organic materials and decreased losses through adoption of improved management practices for reducing the soil respiration increase the net sink of C in soils. Changes in climate are likely to influence the rate of accumulation and decomposition of SOM, both directly through changes in temperature and moisture, and indirectly through changes in plant growth and rhizodepositions (Das and Hati, 2010).

Increased temperature and frequent rainfall stimulates microbial activity. Hence there will be an increase in mineralization or decomposition of organic residues in the soil releases the CO$_2$ to atmosphere. Increased atmospheric CO$_2$ increases plant water use efficiency (WUE) results increase in biomass production per mm of available water (Kimball, 2003). But the decomposition rates are greater than primary production under increased water deficits. So it causes the reduction of biomass accumulation and depletion of soil C and decrease the C: N ratio of soil (Rosenzvig and Hillel, 2000; Krischbaum, 2000; Lal, 2004). Drier conditions favour the organic carbon reduction and thus reduction in annual and perennial vegetation. During summer periods increased risk of fires destroys vegetation cover leads to rapid defoliation and conversion of carbon stores to atmospheric carbon (Hennessy et al., 2005). Over all climate change has the negative impact on soil organic carbon and its storage in tropical climate. Globally, the net effect of climate change will be to decrease stocks of organic carbon in soils, thus releasing additional CO$_2$ into the atmosphere and acting as positive feedback, further accelerating climate change.

Increased temperature and frequent rainfall will have positive influence on C storage in the soil. While some parts of the sub-tropics where scares rainfall and higher temperature induced drought and desertification will reduce the vegetation cover and carbon sequestration potential of the soil. Climate change mediated soil organic matter dynamics is a complex process that influenced by many factors and processes will differently interplay in long term basis is unpredictable.

**Nitrogen dynamics**

The amount and distribution of N in different forms in the soil depends upon a number of inter linked input processes, transformations and loss processes. In many natural and semi-natural ecosystems, the atmospheric N deposition has increased over the years. As compared to estimated inputs of 1-3 kg N ha$^{-1}$ yr$^{-1}$ in the early 1900s (Goulding, 1998), the atmospheric N deposition rates of 20-60 kg N ha$^{-1}$ yr$^{-1}$ in non-forest ecosystems in Western Europe, and up to 100 kg N ha$^{-1}$ yr$^{-1}$ in forest stands in Europe or the USA have been observed (Bobbink et al., 2002). While there has been an increase in deposition rate across all the biomes at both temperate and tropical latitudes, the increase is the greatest in the northern hemisphere temperate ecosystems (Table 3). The high deposition rates are probably driven by biomass burning, soil emissions of NOx and NH$_3$ as well as lightening production of NOx.
Table 2. Pre-industrial and contemporary N depositions (Tg N yr\(^{-1}\)) onto different hemisphere (Source: Adapted from Holland et al., 1999)

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Pre-industrial</th>
<th>1990s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern hemisphere</td>
<td>4.03</td>
<td>26.65</td>
</tr>
<tr>
<td>Southern hemisphere</td>
<td>1.87</td>
<td>1.76</td>
</tr>
<tr>
<td>Tropical</td>
<td>7.64</td>
<td>15.55</td>
</tr>
</tbody>
</table>

The deposited N besides impacting a number of processes in soil greatly modifies the global C and N cycles. While deposition of N to agricultural or croplands could serve as a source of nutrient, it could also adversely affect several processes in the soil. Nitrogen deposition can lead to reduction in biodiversity, soil acidification, and increased nitrous oxide emissions from soils. It also altered the balance of nitrification and mineralization/immobilization, and increased NO\(_3\) leaching resulting in contamination of surface and under ground water bodies. Increasing temperature in combination with aerobic conditions increases nitrification increases the mineral nitrogen in the soil. Episodic rainfall in arid and semi-arid region increases the risk of nitrate loss due to leaching. In anaerobic conditions, the rate of denitrification will also increase the loss of nitrogen as N\(_2\)O or N\(_2\) which reduces the plant available nitrogen in soil. Depressing effects of temperature on symbiotic nitrogen bacteria also reduce the nitrogen fixation and increase the dependence of artificial nitrogen sources. The models simulating denitrification in soils indirectly address the impact of climate change by including adjustment functions for substrate availability (such as NO\(_3\) concentration), soil temperature and moisture to calculate actual denitrification rate from the potential rate. The main problems with the models for simulating N regime of agricultural soils are that these do not explicitly include the effect of atmospheric N deposition and changes in ambient CO\(_2\) concentration. So long term effect of climate change on nitrogen dynamics is complex and unpredictable.

**Soil fertility and nutrient availability**

Most of climatic studies have reported the influence of climate change on terrestrial ecosystems. As a result of elevated soil and water temperature, there are significant changes in soil processes such as net nitrogen mineralization and soil respiration which would have profound implication for ecosystem functioning by affecting changes in nutrient availability and carbon storage (Kirschbaum, 1995). Across the range of ecosystem types, warming was found to increase soil respiration by mean of 20\%, where as net N mineralization increased by an average of 46\% (Rustad et al., 2001).

Table 3. Potential interactions of global change variables on soil processes with mineral stress (adopted from Samuvel and Jonathan, 2010)

<table>
<thead>
<tr>
<th>Process</th>
<th>Global change variables</th>
<th>Interaction with mineral stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion</td>
<td>Heavy precipitation and drought</td>
<td>Losses of soil nutrients and SOC</td>
</tr>
<tr>
<td>Mass flow</td>
<td>Drought, temperature, RH, CO(_2)</td>
<td>NO(_3), SO(_4), Ca, Mg, and Si</td>
</tr>
<tr>
<td>Root growth &amp;architecture</td>
<td>Drought, temperature, RH, CO(_2)</td>
<td>All nutrients, especially P and K</td>
</tr>
<tr>
<td>Mycorrhizas</td>
<td>CO(_2)</td>
<td>P, Zn (VAM) and N</td>
</tr>
<tr>
<td>Soil microbes (N cycling)</td>
<td>Drought, soil temperature</td>
<td>N</td>
</tr>
<tr>
<td>Biological N fixation</td>
<td>Drought, soil temperature</td>
<td>N</td>
</tr>
<tr>
<td>Soil redox status</td>
<td>Flooding</td>
<td>Mn, Fe, Al and B</td>
</tr>
<tr>
<td>Soil leaching</td>
<td>Heavy precipitation</td>
<td>NO(_3), SO(_4), Ca, Mg</td>
</tr>
<tr>
<td>Plant phenology</td>
<td>Soil temperature</td>
<td>P, N, K</td>
</tr>
<tr>
<td>Soil organic carbon status</td>
<td>Soil moisture, temperature, CO(_2)</td>
<td>All nutrients</td>
</tr>
<tr>
<td>Salinization</td>
<td>Precipitation, soil temperature</td>
<td>Na, K, Ca, Mg</td>
</tr>
</tbody>
</table>
Accelerated decomposition and mineralization would bring more N in the soil and would have positive impact on N supply to crops and vegetation. However the rate of denitrification is very sensitive to soil temperature and its rate increases rapidly from 2 °C to 25 °C, and the rate of denitrification increases gradually after 60 °C. The increased microbial and root activity in the soil would entail higher CO₂ partial pressure in soil air and CO₂ activity in soil, hence increased rate of plant nutrient release from weathering of soil minerals particularly P, K, Mg and micronutrients. Similarly, the mycorrhizal activity would lead to better phosphate uptake. At higher temperature, the process of production of less soluble reaction products of P with soil components and P retention in soil increases. Increasing soil temperature also affects availability of K to plants. Consequently rapid increase in soil organic matter dynamics and soil microorganisms may cause the competition for plant nutrients. The changes in global variables that affect the various soil process lead to mineral stress are presented in table 3.

**Soil biodiversity and enzyme activity**

Temperature, precipitation and vegetation changes considerably influence the microbial community and their activity in the soil. Particularly under condition of elevated CO₂ and changed temperature and moisture regimes, soil biodiversity and its function are expected to change. Elevated CO₂ elicited a 47% average increase in mycorrhizal abundance and that mycorrhizae were stimulated disproportionately more than roots (percentage colonization increased by more than 30%) (Treseder, 2004). Another meta-analysis reported that the mass of ectomycorrhizal (EM) fungi increased by 34% in CO₂- enriched environments, whilst that of AM (endomycorrhizal) fungi increased by 21% (Alberton et al., 2005). Over all, changes in plant growth and rhizodepositions have an impact on soil microbial activity. However, reduced soil moisture creates unfavourable environment for microflora, microfauna as well as macrofauna like earthworms, termites, arthropods etc.

Factors influencing soil microbial activity exert control over soil enzyme production and nutrient availability (Sinsabaugh et al., 1993). Warming and drought affect the activity of the soil enzymes involved in C and N mineralization in the mid and long term. In a recent study conducted in Mediterranean shrublands by Sardans et al., (2008) revealed that warming increased soil urease activity by 10% in the study period (1999-2005), and increased β-glucosidase activity 38%. Soil urease and β-glucosidase activities were positively correlated with soil temperatures in winter and negatively in summer. Drought reduced soil protease activity (9%) and did not affect β-glucosidase activity. They have observed that warming and drought have changed some soil enzyme activities related to P turn-over in some year seasons (Sardans et al., 2006). The effects of warming and drought on soil enzyme activities were due to a direct effect on soil temperature and soil water content and not to changes on soil organic matter quantity and nutritional quality (Sardans et al., 2008).

**Soil water dynamics**

Climate change can affect soil hydrological cycle through multiple pathways because the effects of many climatic variables such as precipitation, temperature, and CO₂ concentration as well as their interactions are often complex, dynamic, and nonlinear. The rise in temperature increase the rate of evapotranspiration causes soil drying and lowering of ground water table. Rapid melting of snow and large glaciers of Himalayas may increase the stream flow of some north Indian rivers, increase the availability of water for crop growth for short period but in the long run the scenario may change. The decrease in atmospheric precipitation in some parts will result in a decrease in water infiltration and water storage in the soil. The extreme variability in precipitation pattern, spatially and temporally may lead to higher surface run-off and erosion which radically modify the field water balance and its component. The actual impacts of individual
variables and/or their interactions, which may differ seasonally and geographically, can be adequately assessed.

**Soil structure**

Interaction between soil organic matter storage and aggregate stability is complex. Increase in organic matter production due to induced biomass production will improve soil aggregation and consequently water transmission and retention properties of the soils of tropics and sub-tropics. However, in areas of predicted rainfall reduction particularly in semi-arid tracts water stress will counteract biomass production and consequently soil aggregation will also be affected. The most important direct impact on soil aggregation are rain drops, surface runoff, erosion and filtering water, and indirect influences act through the vegetation pattern and land use practices. Increased rainfall intensities where rain droplet impact causes surface sealing on sodic soils. Climate induced changes in rainfall intensities and volume increase the risk of surface runoff and water erosion resulting in washing out of stable soil aggregates. The prolonged dryness reduces the microbial activity and vegetation cover in the soil. In turn, this reduces the release of root residues and organic matter accumulation in the soil, thus affect the soil aggregate formation. The changing land use pattern like conversion of forest and pasture lands to agricultural use causes the soil degradation and risk of destruction of soil structure, compaction, and further increases the emission of greenhouse gases to the atmosphere.

**Soil reaction (pH)**

Climate change might not produce any immense rapid pH changes in the most of world soils. Less net leaching of bases slows soil acidification process. Exceptions might be found in potential acid sulphate soils, extensive in some coastal plains and estuaries, such as in Kutanad, Kerala and in Sunderban, Kolkata if they become subject to increasingly long dry seasons. Sometimes pH of these soils may temporarily reach 2.5 to 3.5 upon oxidation. This then buffers the pH generally between 3.5 and 4 in the long run by clay fraction decomposition. Thus the extreme acidity and aluminium toxicity may last between less than a year to several decades.

In calcareous soils, soil reaction may range between about 8.5 and 7 depending on the partial pressure of CO$_2$ in the soil. This range is maintained against leaching of basic cations by the different soil processes as long as a few per cent of finely distributed lime remain. Buffering in non-calcareous soils is less strong, but depends on the cation exchange capacity of soil and its pH. In soils with variable-charge surfaces of the clay fraction, buffering capacity decreases with acidification. In conditions where leaching is accelerated by climate change, soil acidification takes place rapidly because of acid rain. The low pH of rain water steadily depletes basic cations, but a pH change may start, or may become more rapid, once certain buffering pools are nearly exhausted.

**Soil erosion and runoff**

Climatic factors have become more significant in recent times due to rapid climate changes induced by intensive anthropogenic activities affecting our ecosystem in multiple ways. It is projected that by the end of the 21st century rainfall over India will increase by 15-40%, and mean annual temperature will increase by 3-6°C (NATCOM, 2004). Changes in precipitation particularly increased rainfall intensities increase chance of run-off and soil erosion on crop and pasture lands. The recent unprecedented rainfall leading to floods in 13 districts of North Karnataka and estimate made after the calamity revealed that nearly 287 million tonnes (mt) of top soil, 8 lakh tonnes of soil nutrients and 39 lakh tonnes of soil organic matter were washed away and nearly 57.5 mt of soil microbial biomass were lost from the region during this short period (Natarajan et al., 2010). Increase in frequency of extreme weather events will increase the run-off and erosion losses of the fertile surface soil in a considerable part of humid tropics. For each 1% increase in annual rainfall increases erosion by approximately 1.7%. On the other hand drought
induced losses of biomass and vegetative land cover causes the removal of top soil and loss of fertility due to nutrient export. Changes in wind regimes where increased winds increase chance of soil erosion, particularly on fine textured cropping soils. Erosion potential for crop lands is more than in pasture and rangelands depending on climate change scenarios.

**Soil salinization/sodification**

Soils in most developing countries are expected to significant risk of climate-induced physical and chemical degradation. In most parts of Asia, forest is shrinking, agriculture is gradually expanding to marginal lands and land degradation is accelerating through nutrient leaching and soil erosion. About 20% of the agricultural land in Asia has been degraded over the last several decades (Foley et al., 1998). Unsustainable practices in irrigation and production, in conjunction with climate change, have lead to increased salinization of soil and nutrient depletion. An estimated 950 Mha of salt-affected lands occur in arid and semi-arid regions, constituting about 33% of the potentially arable land area of the world. Globally, some 20% of irrigated land (450,000 km^2) is salt-affected, contributing about 2,500–5,000 km^2, and lost its production every year as a result of salinity (UNEP, 2008).

In arid and semi arid environments, increased evaporative losses increase capillary rise of salt relative to leaching, bringing salts closure to surface increase transient salinity (Rengaswamy, 2002). Abate of secondary salinization due to increased dewatering of subsoil and fall in ground water level due to low rainfall increase the concentration of salts in the soil solution, inducing osmotic stress in the root zones.

The rise of eustatic sea level by the consequence of global warming increases the chance of sea water intrusion in the major costal lands turning them not suitable for cultivation.

**Soil Contamination**

In the urge to attain the food security, adoption of improved management and intensive agricultural practices increased the usage of large amount of fertilizers and farm chemicals. Impact of global warming will likely to demand more of these artificial chemical sources (Manoj Kumar, 2011). These practices leave their foot prints in the form of heavy metal pollution via application of fertilizers and pesticides and pesticide pollution through higher residual accumulation. On the other hand, Climate change mediated drought and prolonged dry conditions slow the solubility, mobility and break down of these contaminants further aggravates the severity of soil pollution and degradation risks.

**Conclusions**

The prediction of potential consequence of changing atmospheric CO₂ on soil processes is a very difficult task because of its complex nature, interactive influence on soil-water, vegetation and land use. Few studies have been conducted for assessing the effect of elevated CO₂, changing temperature and rainfall pattern on soil processes. They often subject to great spatial and temporal variations within ecosystems. Further the long term effect of CO₂ change in any ecosystem processes are not predicted or measured in short term studies. Elevated atmospheric CO₂ induced changes in atmospheric temperature and hydrological cycle are expected to subject soils to significant risk of climate induced physical and chemical degradation. All these issues have to be addressed. To mitigate adverse impact of climate change urgently we need to undertake measures to increase our adaptive capacity. Sustainable agricultural practices, integrated nutrient management practices should be adopted. Climate change compatible soil management systems to be identified and practiced. Development and effective implementation of policies to restore soil carbon and increasing fertilizer and water use efficiency may improve the soil ecosystem some extent. Due to many uncertainties in global climate changes (direction, rate, seasonal and geographical distribution) and in the prediction of their environmental, ecological, economical and even social consequences, more detailed, integrated multidisciplinary studies are required to give
an exact scientific basis for the adaptation or mitigation of the unfavourable consequences of climate change.

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4. Effect of elevated CO\textsubscript{2} on photosynthesis and yield of crops

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It is an indisputable fact that global CO\textsubscript{2} levels are rising. Estimates suggest that CO\textsubscript{2} is increasing at the rate of 1.5 ppm per year. Thus by the end the 21\textsuperscript{st} century, CO\textsubscript{2} levels could be twice the current levels.

The result of increasing CO\textsubscript{2} will have both direct and indirect effects on plant growth, survival, and distribution. There are two reasons, both of which can affect plants and consequently all living organisms. One is that CO\textsubscript{2} increases are predicted to cause global warming through a process called the greenhouse effect. Secondly, CO\textsubscript{2}, like SO\textsubscript{2} and NO\textsubscript{2}, can be viewed as a nutrient for plants since it is required for photosynthesis. Thus rising CO\textsubscript{2} levels can affect plant growth directly by affecting photosynthetic rates, and indirectly by causing an increase in temperatures.

Let’s first consider the direct effect of CO\textsubscript{2} on plants and then consider the aspect of global warming. Basically there are three strategies that plants use to fix CO\textsubscript{2}. These include what are commonly referred to as the C\textsubscript{3}(Fig.1), C\textsubscript{4}(Fig.2), and CAM(Fig.3) (crassulacean acid metabolism) photosynthetic pathways.

The designations C\textsubscript{3} and C\textsubscript{4} represent the number of carbon atoms associated with the first stable intermediate formed after CO\textsubscript{2} is initially fixed in the respective metabolic processes. C\textsubscript{3} plants are considered to be the most primitive evolutionarily, and CAM plants perhaps transitional to the more advanced C\textsubscript{4} plants. These different plants are distributed latitudinally on a global basis with ranges overlapping. Very simplistically, C\textsubscript{4} plants exist predominantly in the tropics and equatorial regions, C\textsubscript{4}/C\textsubscript{3} mixes occur in temperate areas, and C\textsubscript{3} plants predominate in higher and polar latitudes. CAM plants are typically associated with dry, desert environments. These three groups of plants differ in the ways that they acquire and process the CO\textsubscript{2} used in photosynthesis. All three have what is called the Calvin cycle reactions (C\textsubscript{3} reactions), where CO\textsubscript{2} is ultimately fixed to form simple sugars. The three groups differ as to how CO\textsubscript{2} is “fed” to the Calvin cycle and when. C\textsubscript{4} plants have essentially two mechanisms that fix CO\textsubscript{2} the Calvin cycle and the so-called C\textsubscript{4} metabolic reactions, or Hatch and Slack photosynthesis. The C\textsubscript{4} reactions are associated with the outer bundle sheath layer that surrounds the vascular bundles in the leaf. The C\textsubscript{3} reactions are localized in the mesophyll cells beneath the bundle sheath cells and are directly adjacent to the vascular tissue. This type of vascular arrangement of photosynthetic cells is referred to as Krantz anatomy and is unique to C\textsubscript{4} plants. The C\textsubscript{4} pathway, localized in the bundle sheath cells, initially fixes CO\textsubscript{2} using the enzyme phosphoenolpyruvate carboxylase (PEPcase) and forms either malic or aspartic acid, which is then transported from the bundle sheath to the mesophyll layer. There these acids are decarboxylated, releasing previously fixed CO\textsubscript{2} to the Calvin cycle, where it is fixed a second time by rubisco with the subsequent formation of sugars. The anatomical structure of the C\textsubscript{4} plant thus represents a type of pumping system where to can be transported to the mesophyll via malic and aspartic acid and maintain a relatively high partial pressure of CO\textsubscript{2} which is near saturation levels for rubisco in mesophyll where the C\textsubscript{3} reactions occur. Why is this important? It is important because rubisco, in C\textsubscript{3} plants (Calvin cycle only) can fix not only CO\textsubscript{2} but also O\textsubscript{2}. If O\textsubscript{2} is fixed, less carbon is incorporated into the manufacturing of sugars and, in some carbon is lost since the molecules formed as a result of oxygenase activity enter the photorespiratory pathway (Fig 4) which ultimately leads to the loss of additional carbon as CO\textsubscript{2} during the process.
Calvin Cycle (Dark Reactions of Photosynthesis)

Fig. 1. C₃ pathway of CO₂ fixation

Fig. 2. C₄ pathway of CO₂ fixation (Hatch and Slack cycle)
Thus, the Krantz anatomy design, in C₄ plants, provides a mechanism whereby the CO₂/O₂ ratio is kept high and photorespiration is minimized or prevented. Also, the enzyme PEPcase does not exhibit oxygenase activity and is saturated at normal ambient CO₂ concentrations. In C₃ plants, photorespiration is high. The reason for this is that the Krantz anatomy and C₄ reactions do occur. All photosynthetic cells in C₃ plants fix carbon using the Calvin cycle (C₃) pathway only. Thus, in C₃ plants, during high rates of photosynthesis when O₂ is produced in the light reactions of photosynthesis, the CO₂/O₂ ratio shifts in favor of O₂, which supports more photorespiration. Loss estimates of net carbon fixed been as high as 20-50% of previously fixed carbon when plants are grown at ambient CO₂ levels. Crassulacean acid metabolism (CAM) plants are unique in that they
close their stomates during the day and fix CO₂ at night. This mechanism slows desert plants to conserve water during the day while fixing carbon at night. Although CAM plants do not have the typical Krantz anatomy, they do have a mechanism similar to that in C₄ plants for fixing carbon at night, in that PEPcase is involved in the initial fixation process, and formation of malic acid and aspartic acid occurs. These acids are typically stored in the vacuole but are decarboxylated during the day to support the Calvin cycle. Thus, it appears that C₃ plants have developed a spatial strategy (Krantz anatomy) for increasing photosynthetic efficiency, while the CAM plants have developed a temporal strategy (stomatal opening at night). However, what little information is available for CAM plants suggests that they can benefit from increased nocturnal CO₂ levels.

Essentially, what all of the foregoing is trying to establish is that CO₂ is limiting in C₃ plants and that elevated CO₂ levels most likely would stimulate photosynthesis and hence growth in C₃ plants and possibly CAM plants. The stimulation of C₃ plants is a well-known fact that has been established for many years and has been used successfully to increase production in greenhouse operations. It is also known that C₄ plants do not respond to elevated CO₂ levels the way C₃ plants do. This relates, as previously explained, to the fact that the C₃ fixing enzyme, rubisco, is kept at or near CO₂ saturation as a result of the anatomical configuration and associated C₄ reactions surrounding the mesophyll where the C₃ reactions are restricted. So the question remains how will increasing CO₂ affect plants and plant communities? Some researchers predict that most plants will benefit greatly because increased CO₂ will stimulate growth and plant productivity. In fact, when experiments using C₃ plants are conducted with twice the current levels of CO₂, photosynthesis can be increased as much as 50%. It has also been observed that some plants maintain these high rates of photosynthesis for only short periods of time before dropping back to lower but still elevated levels of photosynthesis.
Carbon pools, Carbon management indices and soil carbon dynamics

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Soil carbon

In most soils (with the exception of calcareous soils) the majority of C is held as soil organic carbon (SOC). The term soil organic matter (SOM) is used to describe the organic constituents in the soil (tissues from dead plants and animals, products produced as these decompose and the soil microbial biomass). The constituents of SOM can be divided into non-humic substances, which are discrete identifiable compounds such as sugars, amino acids and lipids, and humic substances, which are complex largely unidentifiable organic compounds. Organic compounds, both humic and non-humic substances contain carbon, oxygen and hydrogen and can also contain nitrogen, phosphorus and sulfur. Thus, soil organic matter, of which carbon is a major part, holds a great proportion of nutrients, cations and trace elements that are of importance to plant growth. On application to soil, the SOM improves the different soil properties. It increases the cation exchange capacity (CEC), water-holding capacity of sandy soil and it contributes to the structural stability of clay soils by helping to bind particles into aggregates. It prevents nutrient leaching and is integral to the organic acids that make minerals available to plants. It also buffers soil from strong changes in pH. It is widely accepted that the carbon content of soil is a major factor in its overall health. It has long been encouraged that farmers adjust practices to maintain or increase the organic component in the soil—on one hand and discourage practices that hasten oxidation of carbon, such as burning crop stubbles or over-cultivation.

The addition of organic carbon improves soil structure, texture and tilth (Hati et al. 2008), activates a very large portion of inherent microorganisms (Goyal et al. 1993), and dilutes the toxic effects of pesticides (Gaur 1975). Application of only organic sources to the system resulted in highest build up of organic carbon content (Lakaria et al. 2009). In a long-term crop experiment with different crops near Linz, Austria, Ros et al. (2006) found that compost treatment increased soil organic carbon at all depths from 11 g kg\(^{-1}\) for control soil to 16.7 g kg\(^{-1}\) for the case of sewage sludge compost. A 10 year experiment of legume cover crop incorporation with rain-fed Alfisols in southern India showed that biomass incorporation improved mean soil organic carbon content by 24 % over fallow (Venkateswarlu et al. 2007).

Soil organic carbon pools/fractions

Soil organic matter is made up of different pools which vary in their turnover time or rate of decomposition. Although the amount of soil organic carbon in soils of India is relatively low, ranging from 0.1 to 1 % and typically less than 0.5 %, its influence on soil fertility and physical condition is of great significance (Swarup et al. 2000). The cause of low level of organic carbon in Indian soils is primarily due to high temperature prevailing throughout the year. Land cover/land use are important factors controlling the amount and composition of SOM fractions at the aggregate level. The distribution of SOC within different pools is an important consideration for understanding its dynamics and diverse role in ecosystems (Jenkinson 1990). Most of the organic C in soil (60–70%) resides in the passive pool, with turnover times ranging from centuries to millennia. Approximately 20 to 40% of SOC is in the slow pool, with decadal turnover times, while <5% of the SOC is found in the rapidly cycling active fraction, with turnover times ranging from hours to months (Follett, 2001 and Burke et al. 1989). Parton et al. (1987) observed that active pools of soil organic carbon consist of living microbes and microbial products along with soil organic carbon/matter with a short turn-over time (1 to 5 years); a pool of carbon and nitrogen (slow pool) that is physically protected and/or in chemical forms has more resistance to
decomposition. With an intermediate turn-over time (20 to 40 yrs); a fraction i.e. chemically recalcitrant (passive SOC) with the longest turn-over time (200 to 1500 yrs); a structural pool that has 1 to 5 year; and metabolic pools that have 0.1 to 1 year turn-over time. The labile pool results from the addition of fresh residues such as plant roots and living organisms, whilst resistant residues which are physically or chemically protected are slower to turn over. The protected humus and charcoal components make up the stable soil organic matter pool which can take 00’s to 000’s of years to turnover.

Water soluble carbon (WSC) or dissolve organic carbon (DOC) is one of the most actively cycling carbon pools and is of significance for transport of nutrients, such as nitrogen, phosphorus, sulphur. Metals and pollutant in soil. It also involved in the biogeochemistry of carbon and redistribute organic. Carbon with soil depth several studies have attempted to characterize and measure internal fluxes of WSC through forest ecosystems, such as. Measurements of WSC in precipitation fall and soil water. It is necessary to understand the global carbon cycle since marine and terrestrial ecosystems are huge WSC reservoirs compared to the atmosphere and it is important to know how fast these reservoirs can influence water acidity, the mobility and toxicity of metals, and nutrient availability. Fertilization has also been shown to cause a dramatic increase in WSC liability dissolved organic matter seasonal fluctuation in its concentration is commonly encountered (Sarathchandra et al. 1997 and Murphy et al. 2000). Leinweber et al (1995) observed that long –term fertilization with NPK and farmyard manure resulted in significantly greater hot water extractable organic carbon than in control plots. Only 10-40 % (typically about 20% ) of dissolved organic matter (DOM) is readily degradable by soil microflora (jandl and sollins 1997, Smolander et al .2001 ) the bulk of DOM is present as soil humic material is relatively . Recalcitrant (Boyce and Groffman 1996, Yano et al 2000). Nonetheless, the flux of metabolizable C passing the labile degradable fraction is a major determinant of soil microbial active.

Traditionally, organic carbon (Walkley and Black method) or TOC were used in the studies on SOM dynamics. But changes in total organic carbon (TOC) as a result of management practices or land use are small in short period of few cropping seasons and hence seldom detectable because of high background levels and natural soil variability. In contrast, labile C fractions (readily decomposable; susceptible to microbial breakdown; easily oxidizable pool) generally have high turnover rates (short turnover time) and are sensitive to management – induced changes in SOC. Labile or active C pools fuel soil food web and hence influence nutrient cycling and many other biologically related soil properties. Labile C fractions serve as early and sensitive indicators of management induced change in SOC and hence soil quality and sustainability. The SOC fractions such as microbial biomass carbon (Jenkinson and Powlson, 1976), Light fraction organic carbon (Six et al., 1998), Particulate soil organic carbon (Cambardella and Elliott, 1993), Mineralizable carbon (Anderson, 1982) and Permanganate oxidizable soil carbon (POSC) (Blair et al, 1995 and Weil et al. 2003) are all labile fractions of soil organic carbon.

The labile fraction generally consists of plant roots and non-decomposed plant residues, the soil micro fauna and macro fauna, light fraction or macro-organism matter, water soluble organic matter and matter and other non humic organic material Management practices that increased SOC generally lead to increase in SMBC hot water soluble organic carbon and carbohydrate carbon though some labile organic carbon pools respond more sensitively to tillage or rotation practices than others ,all responded in a similar fashion ridge tillage and rotation with corn significantly increased SOC and labile organic carbon contents of adjacent soil sample with different cropping histories as affected by application of fertilizers and crop residue and the growth of wheat and they reported increased labile carbon after wheat they also reported that labile carbon expressed as a percentage of total carbon in the soil ranged from 9.0 to 19.7% for the cultivated soil and from 30.8 to 26.1 for native soil. The amount of labile carbon influences both
tactility mass of micro-organisms (microbial biomass) in soil. The micro-organisms’ capacity to release plant-available N is influenced by the quality of organic matter inputs, with net release of nitrogen from the labile soil organic matter occurring at a C:N ratio below about 22:1. High inputs of more recalcitrant residues can increase the ratio of carbon to nitrogen in this labile fraction and can result in net immobilization of nitrogen, making it unavailable for plant uptake. The C: N ratio of a residue decreases as the extent of decomposition increases and becomes more nutrient rich over time. The labile carbon pool has been to shown to be influenced by the retention of stubble residues, with a decline in nitrogen supply of up to four kg/ha/day on removal of these residues. Green manure crops and phase pastures are an ideal way of providing soil with a “pulse” of labile carbon that can have benefits over several years, but in most Australian farming systems crop roots, stubble and animal by-products are the usual carbon sources. In tropical soils, increasing amounts of labile carbon have been associated with higher grain yields.

**Impact of carbon addition**

Inert carbon is largely unavailable to microorganisms and is associated with highly weathered soils and historical burning. Although this carbon has an important role in the exchange of cations and water holding capacity, it is generally not associated with rapid microbial turnover of nutrients in agricultural soils. By contrast, the labile (bio-available) pool of carbon is primarily influenced by ‘new’ organic matter (originating from plants and/or animals) contributed annually and has a significant role in microbial nitrogen turnover and supply. Since labile carbon turns over relatively rapidly, it is considered a more sensitive indicator of changes in soil quality and function than the percentage of total carbon which includes the more inert fractions. It was reported that after 17 years of continuous stubble burning in a low rainfall environment in Western Australia; only small changes were measured in total soil organic Carbon. This compares to the smaller, more labile carbon pools and Microbial biomass (MBC) fractions which demonstrated differences between treatments of 31 to 43%. The contribution of these labile components to the total soil organic matter pool influences the biological fertility status of the soil. In a range of soils have a measurable total soil organic matter pool of 10 t/ha (equivalent to 1.0% organic carbon at a bulk density of 1.0). However, the soil with 50% of its total soil organic matter present as a labile pool, suggests a more biologically active soil with greater potential for nutrient turnover than the soil with just 5% of its total organic matter pool ‘bio-available’.

The amount of SOC depends on soil texture, climate, vegetation and historical and current land use/management. Soil texture affects SOC because of the stabilizing properties that clay has on organic matter. Organic matter can be trapped in the very small spaces between clay particles making them inaccessible to micro-organisms and therefore slowing decomposition. In addition, clay offers chemical protection to organic matter through adsorption onto clay surfaces, which again prevents organic matter from being decomposed by bacteria. Soils with high clay content therefore tend to have higher SOC than soils with low clay content under similar land use and climate conditions. Climate affects SOC amount as it is a major determinant of the rate of decomposition and therefore the turnover time of C in soils. In temperate grassland, high organic matter inputs combined with slow decomposition rates (determined by climate) lead to high SOC amounts, whereas in tropical areas, decomposition and the turnover of SOC tend to be faster.

**Why soil organic carbon management?**

Greatest challenge in 21st century is to feed the ever increasing population. About 790 million people will not have enough food to eat and the food insecurity will mainly be confined to the developing countries. Overexploitation and degradation of natural resources is one of the major constraints that agriculture faces worldwide. In India, currently the gap between annual output of nutrients (NPK) from soil due to crop removals and the nutrient inputs from external sources (fertilizers) is negative by about 10 million tonnes (Sundaram 2001). Increasing soil
carbon is not a straightforward matter—it is made complex by the relative activity of soil biota, which can consume and release carbon and are made more active by the addition of nitrogen. Land use has a direct bearing on the soil organic carbon content of soil. Practices such as green manuring, inter cropping with pulses, addition of crop residues, FYM, etc. improves the content of soil organic carbon. At the same time there are practices that result in the decline in soil organic carbon content in soil. These include excessive tillage, burning of residues, residue removal and non-manuring of soils for long period of time. Manuring and fertilizer application also have significant impact on the species diversity of bacteria and fungi. They cause significant changes in the microbial populations which are largely mediated through changes in soil pH. Sharma et al (1983) reported that application of nitrogen fertilizers like ammonium sulfate increase the fungal population whereas FYM and NPK application increased the population of fungi, bacteria and actinomycetes. Certain species of micro-organisms like azotobacter are very sensitive to soil acidity while others like nitrosomonas and nitrobacter are more sensitive to erosion of top soil (venkateswarlu, 2000). Such organisms can be used as indicators of degradative processes in soil or the extent of degradation of given soil.

Soil organic matter and its maintenance is important for the long-term productivity in any agro-ecosystems. Organic manures are the most common amendments applied to soil to improve soil quality and crop productivity. These are known to improve soil productivity by influencing soil organic matter (SOM) status. Soil organic carbon (SOC) affects productivity through its effect on soil structure, plant available water capacity, soil buffering capacity, and as a source of plant nutrients. Stable soil structure is in fact a prerequisite for better soil physical environment. The loss of organic matter and the degradation of soil structure can have a deteriorating effect on the soil quality and crop productivity. The SOC turnover is of paramount Importance for sustaining soil quality and long-term productivity of agricultural systems. It is widely accepted that the carbon content of soil is a major factor in its overall health. It has long been encouraged that farmers adjust practices to maintain or increase the organic component in the soil—on one hand, practices that hasten oxidation of carbon, such as burning crop stubbles or over-cultivation are discouraged; on the other hand, incorporation or organic material, such as manuring has been encouraged. Increasing soil carbon is not a straightforward matter—it is made complex by the relative activity of soil biota, which can consume and release carbon and are made more active by the addition of nitrogen. Land use has a direct bearing on the soil organic carbon content of soil.

Management practices

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Organic sources available across the country offer a potential of 15 million tonnes of NPK per year. India is endowed with a vast potential of plant nutrients locked up in organic, biological and industrial by products. However, their use in INM system is limited, because of their alternate utilities as animal feed, fuel and building material. Major crop improvement strategies for
sustainable agricultural production mainly pursue the use of natural processes such as nutrient cycles, biological nitrogen fixation and pest predator relationship in agricultural production. For sustainable agriculture, the main organic resources use for plant nutrients are FYM, compost, crop residues, green manure, bio-fertilizers, legumes, vermin-compost, biogas slurry, etc. Apart from these organic sources utilized for plant nutrients, other sources include soil reserves, human wastes, urban and rural wastes, sewage sludge, tree and aquatic wastes, agro-industrial wastes like press mud, coir pith from coconut, industry, distillery waste, fruit and vegetable wastes, marine wastes, sea wastes and fishmeal, etc.

**Advantages of organic manure additions:**

- Creates optimal conditions in soil for high yields and good quality crops,
- Supply of all the nutrients required by the plants,
- Improvement in the growth and physical activity of the crop plants,
- Improvement in granulation, tilth, aeration, root penetration, and water holding capacity of the soil.
- Also fibrous portion of the roots improve the soil aggregation and permeability of soil.
- The carbon added through manures is a source of energy for the microbes which help in aggregation
5. Mechanisms of Soil Carbon Sequestration and Stabilization

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Introduction

Soil organic matter (SOM) influences most of the soil functions and represents one of the largest reservoirs of carbon on the global scale (Kögel-Knabner et al., 2005). Important SOM mediated processes in soil include mineralization and nutrient supply (N, P, S), improvement in soil aggregation, enhancement of the soil water retention capacity and hydraulic permeability, reductions in energy required for tillage, enhanced soil tilth, and pH buffering. Collectively these influence crop production and environmental outcomes. Approximately 81% of the organic carbon (OC) that is active in the terrestrial carbon cycle is stored in soils (Paustian et al., 2000; Wattel-Koekkoek et al., 2001). Consequently, any change in the size and the turnover rate of soil C pools may potentially alter the atmospheric CO2 concentration and the global climate. Knowledge of dynamics of organic matter in different locations in the soil matrix can provide valuable information, which affects carbon sequestration and other soil properties. Most organic matter present in the soil is in the form of complex aromatic (ring structured) and aliphatic (long chains of condensed) polymers of high molecular weight that are not easily identified. There is no single structure to soil organic matter because it is derived from a wide range of complex biological compounds, and the organic matter has often been reprocessed many times by soil organisms. Extraction of soil organic matter (SOM) fractions has been a long-standing approach to elucidating the roles of soil organic matter in soil processes. Traditional organic matter classifications rely on chemical or physical fractionation. For example, under traditional chemical fractionation scheme soil organic matter has often been separated into fulvic acid, humic acid and humin fractions, depending on its solubility in water, alkali or acid. Because strong acids or alkali may modify the organic matter extracted from soil it is questionable how useful such chemical extracts or fractions are, and the extracted fractions still have a very heterogeneous composition. Approaches that are more modern use less drastic methods such as physical separation into light and heavy fractions (using floatation in a high-density liquid). Several types of fractionation methods are used and all provide information on soil organic matter function. Physical fractionation capture the effects on SOM dynamics of the spatial arrangement of primary and secondary organo-mineral particles in soil while chemical fractionation does not consider the spatial arrangement of the organic matter but the organic fractions thus separated are suitable for advanced chemical characterization of the organic compounds. Three method of physical separation of soil have been used, sieving, sedimentation and densitometry.

Commonly described soil organic matter fractions and pools:

The term fraction is generally used to describe measurable organic matter components whereas the term pool is used to refer to theoretically separated, kinetically delineated components of SOM (Wander, 2004). It is very difficult to summarize the general relationships between kinetically conceived SOM pools and related OM fractions because overlapping terminology is often applied to fractions and pools that are not closely related and this gives rise to confusion (Wander 2004). Some of the terminologies frequently used in SOM fractionation parlances are given below:

The Light fraction:

Light fraction is commonly referred to a plant-like and less stable fraction with high C concentration. It consists of mineral-free OM composed of partly decomposed plant and animal residues, which turnover rapidly and has a specific density that is considerably, lower than that of soil minerals. Light fraction of SOM is not only sensitive to changes in management practices but
also correlates well with the rate of N mineralization. This fraction represents an intermediate pool between undecomposed residues and humified SOM. The importance of light fraction (including free and occluded organic C within aggregates) is widely recognized for its role in the formation and stability of soil structure, especially in the stabilization of soil macroaggregates (>250 mm). The light fraction is normally separated by density fractionation of SOM with a density of less than 1.85 g/cc.

**The Heavy fraction:**

Heavy fraction is a more stable and high-density organo-mineral fraction having lower C concentrations. Heavy fraction contains more processed SOM and can be a major sink for C storage in soil because it has little mineralizable C as is demonstrated by its poor relationship with soil respiration.

**Inter-microaggregate organic matter:**

Inter-microaggregate OM comprises free POM, the light fraction and microbial biomass. It is also known as unprotected or uncomplexed OM. This fraction of OM is neither present as readily recognizable litter components (which are typically > 2 mm) nor is it incorporated into primary organo-mineral complexes. It is recovered by density and size fractionation procedures or combinations thereof. Separation by density in heavy liquids (1.2-2.0 g ml\(^{-1}\)) has been widely used. The inter-microaggregate OM consists mainly of particulate partly decomposed plant and animal residues but can also encompass fungal hyphae, spores, faecal pellets, faunal skeletons, root fragments, and seeds. It is a transitory pool between litter and mineral-associated OM. Its turnover is also slower than that of recently shed litter but faster than that of OM associated with clay and silt.

**Particulate Organic Matter:**

Particulate organic matter (POM) is an active SOM fraction, which supplies nutrients to the growing plant. It is more responsive to changes in agricultural management than total SOM. It is the microbially active fraction of soil organic matter consisting of fine particles of partially decomposed plant tissues. As such, POM was considered as an indicator of soil quality.

a. **Free POM:** Free Particulate Organic Matter (free POM) includes loose organic particles in the soil i.e. not included in microaggregates, and therefore, free POM is also termed inter-aggregate POM. Free POM consists mainly of partly decomposed litter residues (Golchin et al. 1997). However, Six et al. (1998) suggested that free POM represented a mixture of recently deposited crop residues and older uncomplexed OM previously occluded within aggregates but released from degraded aggregates following the depletion of available substrates in the occluded OM. Free POM is more decomposable than occluded POM.

b. **Intra-microaggregate POM:** Intra-microaggregate POM is the POM that is contained within microaggregates with a size limit of 53-250 μm. The distinction between free and occluded fractions of uncomplexed POM is based experimentally on a stepwise dispersion of soil combined with separations according to particle size or density or both. Free POM is recovered from minimally dispersed samples in which microaggregates remain intact, while occluded OM subsequently is isolated after dispersion of microaggregates. SOM present in free microaggregates or in microaggregates within macroaggregates is protected from decomposition.

**Silt and Clay sized SOM:**

Most of the SOM are normally found in silt and clay sized primary organo-mineral separates. Clay generally accounts for over 50% of the SOM, clay and silt (<20 μm) together may account for over 90% (Christensen, 1996). According to Kiem & Kögel-Knabner (2002), organic structures that are not chemically recalcitrant by nature do not contribute to recalcitrant pools.
unless they are affiliated with fine-particle-size separates; exceptions include charcoal, which is highly resistant to degradation and which is recovered in POM fractions. These fractions are slow to mineralize due to physical protection of the organic resource by their association with mineral particles but contribute to soil stability. Measurement of SOM fractions associated with fine-silt and coarse-clay sized separates is often used to estimate size of the stable SOM pool. This fraction of SOM also comes under heavy fraction of SOM.

Protection mechanisms of Organic matter in soils

Mechanisms for C stabilization in soils have received much interest recently due to their relevance in the global C cycle. There are three main mechanisms for stabilization of OM in soil. They are (i) Physical protection, (ii) Chemical stabilization or stabilization by organo-mineral bonding, and (iii) Biochemical stabilization. These three mechanisms basically involve the accessibility of OM to microbes and enzymes, interactions between the organic and mineral compounds and chemical resistance of organic molecules against microbial attack, respectively. If SOM is not protected by one of these mechanisms, it is considered as unprotected SOM.

1. **Physical protection**: SOM can be physically protected against microbial decomposition by soil aggregation. Aggregates physically protect SOM by forming physical barriers between microbes and enzymes and their substrates. The physical protection exerted by macro- and/or microaggregates on POM-C is attributed to (i) the compartmentalization of substrate and microbial biomass and, (ii) the reduced diffusion of oxygen into macroaggregates and especially microaggregates which leads to reduced activity within the aggregates. The inaccessibility of substrate for microbes within aggregates is due to pore size exclusion and related to water filled porosity.

2. **Chemical stabilization or stabilization by organo-mineral bonding**: Chemical stabilization of SOM is due to the result of chemical and physico-chemical binding between SOM and soil minerals (i.e. clay and silt particles) (Six *et al.*, 2002). In addition to the clay content, types of clay (i.e. 2:1 versus 1:1 versus allophanic clay minerals) influence the stabilization of SOM. Under identical annual OM input, a slower SOM turnover, a larger microbial biomass and more OM are expected in soils with high clay content within the same climatic area (Müller & Höper, 2004).

3. **Biochemical stabilization**: It is the stabilization of SOM due to its own chemical composition (e.g. Recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (e.g. Condensation reactions) in soil. Humified OM, i.e. humic acids and humin in particular, represents the most persistent pool of SOM with mean residence times of several hundreds of years (Piccolo, 1996). With humification, plant residues are transformed into more stable forms (humus).

**Significance of physical fractionation:**

The concept behind physical fractionation of soil emphasizes the role of soil minerals in SOM stabilization and turnover. The physical fractionation techniques are considered chemically less destructive and the results obtained from physical soil fractions are considered to be related more directly to the structure and function of SOM *in situ*. The use of physical fractionations in studies of OM turnover in soil has increased steadily over the past two decades. This development arises from an increasing awareness that the turnover of organic matter in soil is due to biological processes under the overall regulation of soil structure and that the availability of substrates to decomposers depends not only on the intrinsic chemical nature of the substrate but also, and perhaps more importantly, on the nature of its association with the soil’s mineral components and its accessibility to the microbes for decomposition.

Spatial and temporal variability in soils reduces the accuracy of SOC stock measurements. In addition, the detection of changes in SOC stocks with management, climate, or land use change
is difficult because of the small magnitude of such changes relative to the large forest SOC stocks. Physical fractionation techniques can augment the detection limits for SOC storage by isolating SOC pools (POM, iPOM etc.) more sensitive to changes in management, climate, or land use.

Physical fractionation is considered less destructive than chemical methods and results obtained with physical fractionation methods are anticipated to relate better to the structure and function of SOM in situ (Golchin et al., 1994b). These techniques have been applied to determine the association of SOM with primary particles and to quantify the amount of particulate organic matter between and within soil aggregates. Physical fractionation techniques can also elucidate soil processes and mechanisms involved in the storage of SOC. It has been established that aggregation increases in less disturbed systems and that organic materials within soil aggregates (especially microaggregates) have lower decomposition rates than those located outside of aggregates. Physical fractionation of SOM is useful for distinguishing specific C pools responsive to management, identifying the physical control of SOM and characterizing the relationship between SOM and size distribution of aggregates.

Physical fractionation methodologies

Much evidence has accumulated to demonstrate that fractionation of soils according to the size and density of particles provides a useful tool for the study of SOM dynamics and distribution. Physical fractionation includes size and density separation of primary organo-mineral particles in whole soil. It allows the separation of free and occluded uncomplexed organic matter and of primary and secondary organo-mineral complexes. A key point in these separations is to achieve adequate soil dispersion to prevent inclusion of micro aggregates of smaller size particles in the silt and sand size separates. The effectiveness of soil dispersion procedures is crucial for density as well as particle size fractionation. In many studies, dispersion is carried out by ultrasonic vibration or ultrasonication. The potential problem associated with the use of sonication prior to physical fractionation is the redistribution of OM among different fractions. Other than sonication, dispersion can also be carried out using wet sieving method with or without application of dispersing chemicals like sodium hexa meta-phosphate. In recent times, dispersion of soil through wet sieving is getting lot of prominence.

Physical fractionation covers a range of different methods, each designed for specific purposes, including combinations of ultrasonic, mechanical and chemical dispersion with size separation using wet or dry sieving and density separation using heavy liquids. Most fractionation schemes attempt to avoid chemical changes in SOM during the fractionation step and distinguish between SOM that is not firmly associated with soil minerals, SOM that is incorporated into primary organo-mineral complexes, and SOM that is trapped within aggregates (secondary organo-mineral complexes) (Christensen, 1996).

Density fractionation is applied to isolate SOM, which is not firmly associated with the mineral part of the soil. Here soil is dispersed in heavy organic liquids or inorganic salt solutions with specific densities typically ranging from 1.6 to 2.2 g/ml. The light fraction is taken to be less decomposed plant and animal residues, whereas the sediment (or heavy fraction) is expected to encompass true organomineral complexes in which SOM is more processed. Density fractionation was earlier relied on organic liquids like, tetrabromoethane (C₄H₈Br₄), bromoform (CHBr₃), tetrachloromethane (CCl₄). The densities of these liquids are most often adjusted by adding ethanol, or chloroform. But the use of aqueous solutions of inorganic salts like Mg₂SO₄, ZnBr₂, NaI and sodium poly tungstate has become increasing popular due to high potential toxicity of halogenated hydrocarbons. Among the inorganic salts sodium poly tungstate is preferred as it less viscous and less toxic than the solutions of ZnBr₂.

Particle size fractions is based on the concept that SOM fractions associated with particles of different size (and therefore also of different mineralogical composition) differ in structure and
function, and therefore play different roles in SOM turnover. Size fractionation may be applied to whole soil samples or to heavy fractions following density fractionation. In size based fractionation methods, different fractions of SOM are separated by a series of sequential sieving. Dry and wet sieving is both applied depending on the purpose of fractionation. Sieving soil into different size classes separates small aggregates or particles from larger particles, which contain SOC that is partially protected from microbial degradation, although not necessarily chemically recalcitrant. The physical fractionation scheme proposed by Six et al. (2000) are given in detail in this manuscript. As per this scheme, the fractionation is broadly divided in to three steps for separation of aggregates as per size and density fractionation.

**Fractionation Scheme I: Aggregate Separation**

The aggregate separation are done by wet sieving the soil through a series of three sieves (2000, 250, and 53 µm) to obtain four aggregate-size classes (Large macroaggregates (2000-8000 µm), small macroaggregates (250-2000 µm), microaggregates (53-250 µm) and the silt plus clay fraction (<53 µm) (Elliot, 1986).

1. Gently break field-moist soil samples, pass them through an 8-mm sieve and retain them on a 2-mm sieve; and then air-dry the sample.
2. Take 100 g of the sieved soil (2-8 mm aggregate size class) and spread over a 2-mm sieve.
3. Submerse the soil in water for 5 minutes before sieving.
   (This process leads to slaking, which is the breaking of unstable aggregates because of air and pressure build-up inside the aggregates upon submersion in water.)
4. Sieve the soil manually under water by gently moving the sieve 3 cm vertically 50 times over a period of 2 minutes through water contained in a shallow pan.
5. Organic material floating on the water in the 2000-µm sieve was decanted and removed after the 2-min cycle, because it is by definition not considered SOM.
6. Transfer the material remaining on the sieve to an aluminium container/pan and dry at 50-65 °C in a hot air oven.
7. Transfer the water plus soil remaining in the shallow pan after passing through 2000µm sieve to the next finer sieve.
8. Repeat the procedure (2 to 4) for each sieve size class (i.e. 250µm, 53µm etc.).
9. Oven dry the aggregate fractions retained at 50 °C and weigh.
10. Allow the materials smaller than 53 µm to settle, centrifuge and oven dry it for future use.
11. Remove the dry rocks in the largest fraction (>2000 µm) before taking weight.
12. Determine the sand content (> 53 µm) of the aggregates by taking a subsample of aggregates and dispersing them with sodium hexametaphosphate (5 g L⁻¹) and passing them through 53-µm sieve.

**Fractionation II: Free Light Fraction and Intra-Aggregate Particulate Organic Matter (iPOM) by Density Flotation Technique**

The method for separation of the free light fraction (LF) (i.e., particulate organic matter [POM] outside of the aggregates) and iPOM is adopted from Six et al. (1998).

1. Oven dry (110 °C) the aggregate size fractions required for this separation overnight prior to analysis.
2. Cool the oven-dried samples to room temperature in a desiccator.
3. Weigh 5 g subsample and suspend it in 35 mL of 1.85 g cm⁻³ sodium polytungstate in a 50 mL graduated conical centrifuge.
4. Mix the suspended subsample without breaking the aggregates by slow reciprocal shaking by hand (10 strokes). If 10 strokes are not enough to bring the whole sample into suspension, a few more strokes are required rather than increasing the
speed or force of shaking, thereby avoiding the aggregate disruption. The material remaining on the cap and sides of the centrifuge tubes are washed into suspension with 10 ml of sodium polytungstate.

5. Put the sample under vacuum (138 kPa) for 10 min to evacuate air entrapped within the aggregates.

6. After 20 min equilibrium, centrifuge the sample at 3200 r.p.m or 1250 g for 60 min at 20 °C.

7. Aspirate the floating material (free LF) onto pre-weighted 20-µm nylon filter. Rinse thoroughly with deionized water to remove sodium polytungstate.

8. Transfer the sample with the filter into a small aluminum pan and dry at 50 °C.

9. Rinse the heavy fraction twice with 50 mL of deionized water and disperse in 0.5% hexametaphosphate by shaking for 18 h in a reciprocal shaker.

10. Pass the dispersed heavy fraction through a 2000-, 250- and/or 53 µm sieve depending on the aggregate size being analyzed.

The materials remaining on the sieve are iPOM + sand (53-250, 250-2000, and >2000 µm size). Dry the aggregates at 50 °C and weigh and store them for future use. Organic carbon can be determined from the stored samples.

**Fractionation III: Isolation of micro-aggregates within macroaggregates**

Microaggregates contained within small macroaggregates (250-2000 µm) are isolated using the method of Six et al. (2000).

1. Take 10g sub-samples of small macroaggregates (250-2000 µm) and place it on deionized water in a 250µm sieve along with 50 glass beads (4-mm diameter) on a reciprocal shaker.

2. Shake gently so that the macro-aggregates are broken with the aid of glass beads. Allow water to flow continuously so that it carries all the released microaggregates through the 250µm sieve and washes them onto a 53µm sieve. Care should be taken so that the shaking does not break them up. Continuous and steady water flow through the device ensures that microaggregates are immediately flushed onto a 53-mm sieve and are not exposed to any further disruption by the beads.

3. After all the macroaggregates are broken up then sieve the fraction collected on the 53-µm sieve (as described above) to separate the water-stable microaggregates from the silt + clay particles and this will also ensure that the isolated microaggregates are water stable. (The above separation procedure yields three fractions: The materials remaining on the 250 µm sieve consisted of coarse POM, aggregates passing through the 250 µm sieve but retained on the 53-µm sieve are stable microaggregates isolated from macroaggregates and inter-microaggregate POM or fine-POM; and materials passing through 53 µm sieve as clay plus silt particles not associated with stable microaggregates).

4. The inter-microaggregate POM retained together with the microaggregates on the 53-µm sieve could be isolated by density flotation in 1.85 g cm$^{-3}$ sodium polytungstate as described above. After density flotation, the microaggregates are dispersed in 5 g sodium-hexametaphosphate per liter and intra-microaggregate POM is isolated by sieving.

5. Dry all the aggregates and POM fractions at 50-65 °C, weigh and store it in glass jars for further use.

The proportion of microaggregate (53-250 µm) weight within macroaggregates (250-2000 µm) is calculated as:

$$\frac{\text{microaggregate weight} - \text{weight of 53-250 µm sized sand}}{\text{macroaggregate weight} - \text{weight of 250-2000 µm sized sand}}$$

(1)
The weights of macro- and microaggregates are corrected for the sand content of the same size as the aggregates because sand of the same size as the aggregate is usually not a part of an aggregate and should consequently not be weighed as an aggregate.

Fig. 1. Fractionation scheme to isolate aggregate and aggregate-associated organic matter fractions.

cc = very coarse, c = coarse, f = fine, HF = heavy fraction, HMP = hexametaphosphate, i = intra-aggregate, LF = light fraction, mSOC = mineral associated soil organic C, mM = microaggregates within macroaggregates, M = small macroaggregates, POM = particulate organic matter, s + c = silt and clay (Adapted from Six et al., 1998 and 2000).
Fig. 2. Schematic presentation of the microaggregate isolator.

References


Introduction

Soil organic carbon, the major component of soil organic matter, is extremely important in all soil processes. Organic material in the soil is essentially derived from residual plant and animal material, synthesized by microbes and decomposed under the influence of temperature, moisture and ambient soil conditions. Soil organic carbon is important for the function of ecosystems and agro-ecosystems having a major influence on the physical structure of the soil, the soil’s ability to store water (water holding capacity), and the soil’s ability to form complexes with metal ions and supply nutrients. Soil organic matter is a major source of nutrients, a source of cation exchange capacity, contributes to soil structure development and stability, provides water-holding capacity, aeration and favors root penetration (Allison, 1973; Tate, 1987). Loss of SOC can, therefore, lead to a reduction in soil fertility, land degradation and even desertification. Levels of SOC are governed by the difference between inputs of fixed C as organic materials and outputs of several C forms through mineralization, erosion and leaching (Paustian et al., 1997).

Maintenance of soil organic C (SOC) is considered essential for long-term sustainable agriculture, since declining SOC levels generally lead to decreased crop productivity (Allison, 1973). Soil organic matter which determine to a large extent soil workability and availability of water and nutrients to crops, are greatly influenced by management practices. Continuous cultivation in most irrigated and rainfed lands has resulted in the decline of soil physical condition in general, and SOC content in particular. Understanding the response of soil organic carbon (SOC) to environmental and management factors is necessary for estimating the potential of soils to sequester atmospheric carbon. Changes over time in the amount and distribution of SOC fractions with different turnover rates can be estimated by means of soil SOC models (for e.g. Century, RothC, DNDC etc.) Soil organic matter (SOM) turnover models are often used to predict changes in SOC in response to changes in land use, management or climate. Such changes in SOC are associated with an altered CO₂ exchange between terrestrial ecosystems and the atmosphere, and they impact significantly on regional carbon budgets. Apart from understanding the response of soil organic carbon (SOC) to environmental and management factors SOM models could also help farmers in carbon accounting and benefits from carbon market. With the continued development of carbon (C) markets in the world, and the increasing realization that the management of agricultural land is an integral part of that market, the need for soil organic matter (SOM) models to simulate a wider variety of agricultural systems, crops, and crop rotations is increasing. Thus this chapter reviews the various SOM models available to explore these avenues in agroecosystem.

Concepts of soil organic matter pools used in SOM models

As dead organic matter is fragmented and decomposed it is transformed into soil organic matter (SOM). Soil organic matter includes a wide variety of materials that differ greatly in their residence time in soil. Some of this material is composed of labile compounds that are easily decomposed by microbial organisms, returning carbon to the atmosphere. Some of the soil organic carbon, however, is converted into recalcitrant compounds (e.g. organic-mineral complexes) that are very slowly decomposed and thus can be retained in the soil for decades to centuries or more. Following fires, small amounts of so-called ‘black carbon’ are produced, which constitute a nearly inert carbon fraction with turnover times that may span millennia.

Most models are based on several conceptual SOM pools with different turnover rates. These pools can be ascribed to different organic constituents such as plant inputs, decomposers of
the incoming organic material, and storage in various forms of SOM. Typically, the latter is divided into pools that differ from each other by decomposition rates and characteristic stabilization mechanisms, which are linked to rate modifiers. Changes in environmental conditions have different impacts on these pools. But even when stocks are at equilibrium, SOM is in a continual state of flux; new inputs cycle—via the process of decomposition—into and through organic matter pools of various qualities and replace materials that are either transferred to other pools or mineralized. For the functioning of a soil ecosystem, this “turnover” of SOM is probably more significant than the sizes of SOM stocks (Paul, 1984.). An understanding of SOM turnover is crucial for quantifying C and nutrient cycles and for determining the quantitative and temporal responses of local, regional, or global C and nutrient budgets to perturbations caused by human activities or climate change (Trumbore, 1993). The turnover of an element (e.g., C, N, P) in a pool is generally determined by the balance between inputs (I) and outputs (O) of the element to and from the pool. Turnover is most often quantified as the element’s mean residence time (MRT) or its half-life ($T_{1/2}$). The MRT of an element in a pool is defined as 1) the average time the element resides in the pool at steady state or 2) the average time required to completely renew the content of the pool at steady state. The term half-life is adopted from radioisotope work, where it is defined as the time required for half of a population of elements to disintegrate. Thus, the half-life of SOM is the time required for half of the currently existing stock to decompose. The most common model used to describe the dynamic behavior or turnover of SOM is the first-order model, which assumes constant zero-order input with constant proportional mass loss per unit time (Olson, 1963; Jenny, 1980)

$$\frac{dS}{dt} = I - KS \quad (1)$$

Where $S$ is the SOM stock, $t$ is the time, $k$ is the decomposition rate, and $kS$ is equivalent to output $O$. Assuming equilibrium ($I=0$), the MRT can then be calculated as

$$\text{MRT} = \frac{1}{K} \quad (2)$$

And MRT and $T_{1/2}$ can be calculated interchangeably with the formula

$$\text{MRT} = \frac{T_{1/2}}{\ln 2} \quad (3)$$

Eqs. 1 and 2 form the basis for estimates of SOM turnover derived from first-order modeling; the unknown $k$ is calculated as

$$k = \frac{1}{S}$$

By assuming a steady state

$$\frac{dS}{dt} = 0$$

This approach requires estimates of annual C input rates, which can be assumed to be continuous or discrete (Olson, 1963). The input can also be written as

$$I = hA$$

Where $A$ is the annual addition of C as fresh residue and $h$ (the isohumification coefficient) represents the fraction that, after a rapid initial decomposition of $A$, remains as the actual annual input to $S$. An estimate of $h$ is then necessary. A value of 0.3 is commonly used for agricultural crops, but the value can be higher for other materials such as grasses or peat (Buyanovsky and Kucera, 1987; Jenkinson, 1990).

One feature most SOM models share is that they involve one to two labile and/or dynamic pools, two to three physically and chemically protected pools, and one passive or even inert pool (Christensen, 1996). Stabilized SOC is of special importance with respect to long-term CO$_2$ sequestration because it accounts for most of the SOC. Mean residence time of “‘stable”’ or “‘long-lived”’ SOM varies from 250 to 1900 years (Stevenson, 1994). For C to be sequestered in the soil it needs to be protected from microbial degradation within stable microaggregates (<250 mm),
adsorbed on the inner surfaces of clays or be chemically protected in organo-mineral complexes (Lal, 1997). Mean residence time of SOM is affected by the type of clay, in which 1:1 clays like kaolinite have a shorter turnover time than 2:1 clays like smectite (Wattel-Koekkoek et al., 2003). Mean residence time also tends to increase with depth in the soil profile (Paul et al., 2001).

Two most important SOC models followed universally are Century SOC model and Roth C Model. The two models Roth C and Century SOC model differ with respects to the definition and slight deviation of SOM pools which is given in figure 1 and 2.

Partitioning of SOC into fractions in Roth C model

![Diagram](image)

**Fig.1.** Concept of summarizing and splitting SOC fractions and pools in RothC model (Zimmermann et al., 2007)

Where RPM : Resistant Plant Material, DPM : Decomposable Plant Material, BIO : Microbial Biomass, HUM : Humified OM, IOM : Inert Organic Matter rSOC: resistant SOC

- **Structural C (3y)**
- **Metabolic (0.5y)**
- **Active soil C (1.5y)**
- **Slow soil**
- **Passive soil C (100y)**
- **Plant residue**
Models of soil organic matter dynamics reflect the complexity of interactions existing within the soil environment and help evaluate the effects of environmental and management changes at local, regional and global scales on rates of turnover. Most models conceptualize that C resides in soils in several discrete pools showing varying rates of turnover and loss. It is commonly assumed that soil organic matter can be fractionated into a smaller labile pool and one or larger recalcitrant pools, each decaying according to first order kinetics. Using such approaches, several soil organic matter models have been developed, such as SOMM, ITE, Verberne, Century (formulated by WJ Parton et al.), Roth-C (K Coleman et al.), CANDY (U Franko et al.) and DNDC (C Li et al.). RothC and CENTURY are two of the most widely used and tested SOM models. These largely empirical models have generally provided good predictions of C loss in diverse environments, usually over longer time periods. Despite limitations of less reliable short-term predictions and uncertainty of pool homogeneity and uniqueness, these models are helpful in organizing soil C information. When soil organic matter models are integrated within whole ecosystem simulations, better evaluation of ecosystem responses to environmental change can be done. Thus, it is possible to identify the strategies optimizing C sequestration through specific management of soil and vegetation. Several workers have used different SOM models all over world to study effect of change in management practices on dynamics and turnover of soil organic carbon. The user manual of DNDC, RothC and Century model is available free for downloading. Interested users can download it from their respective websites. Table 1 enlists the parameters required by different SOM models of initialization.

Table 1. Minimum data set requirement in different SOM models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RothC model</th>
<th>Century model</th>
<th>DNDC model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly rainfall (mm).</td>
<td>Monthly average maximum and minimum air temperature</td>
<td>Maximum and minimum daily air temperature</td>
<td></td>
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<tr>
<td>Monthly open pan evaporation (mm).</td>
<td>Monthly precipitation</td>
<td>Daily precipitation</td>
<td></td>
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<tr>
<td>Average monthly mean air temperature (°C)</td>
<td>Soil texture</td>
<td>Daily average wind speed</td>
<td></td>
</tr>
<tr>
<td>Clay content of the soil (as a percentage)</td>
<td>Plant N, P, and S content</td>
<td>Soil texture, B.D, pH, clay content</td>
<td></td>
</tr>
<tr>
<td>Soil covers - Is the soil bare or vegetated in a particular month?</td>
<td>Lignin content of plant material</td>
<td>Soil moisture constants at field capacity and permanent wilting point</td>
<td></td>
</tr>
<tr>
<td>Monthly input of plant residues (t C ha(^{-1}))</td>
<td>Atmospheric and soil nitrogen inputs</td>
<td>Soil organic carbon content at surface (0-5 cm)</td>
<td></td>
</tr>
<tr>
<td>Monthly input of farmyard manure (FYM) (t C ha(^{-1})), if any</td>
<td>Initial soil carbon, nitrogen (phosphorus and sulfur optional)</td>
<td>Crop physiological and phenology parameters</td>
<td></td>
</tr>
<tr>
<td>Depth of soil layer sampled (cm).</td>
<td></td>
<td>Types of the crops consecutively planted in a year</td>
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<tr>
<td></td>
<td></td>
<td>Planting and harvest dates</td>
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<td></td>
<td></td>
<td>Maximum biomass production</td>
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<td></td>
<td></td>
<td>Fraction of above-ground crop residue left in the field after harvest</td>
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</tr>
</tbody>
</table>
Some few important SOM models widely used are described below

**DeNitrification-DeComposition (DNDC)**

DNDC is a computer simulation model of C and N biogeochemistry in agro-ecosystems. The model can be used for predicting crop growth, soil temperature and moisture regime, soil carbon dynamics, nitrogen leaching, and emissions of trace gases including nitrous oxide (N$_2$O), nitric oxide (NO), ammonia (NH$_3$), methane (CH$_4$) and carbon dioxide (CO$_2$).

The DNDC model is a 1-D process-based biogeochemical model and consists principally of two components. The first component includes the sub models for soil, climate, decomposition and plant growth. Based on daily climate data, soil physical properties and by considering plant and microbial turnover processes of C, N and water, the soil-climate sub model calculates temperature, moisture and oxygen profiles derived from one-dimensional thermal-hydraulic flow and gas diffusion equations. The respective plant growth sub model (PnET, DNDC crop model) simulates plant growth driven by solar radiation, temperature, water and nitrogen stress, and passes the litter production, water and N demands, and root respiration to the soil climate or the decomposition sub model. The decomposition sub model quantifies the decomposition of organic matter resulting in substrate concentrations of dissolved organic carbon (DOC), NH$_4$ and CO$_2$. The second component includes the sub-models for nitrification and denitrification. The concentrations and fluxes of NO$_3$, N$_2$O, NO and N$_2$ are calculated based on simulated soil microbial activities, which depend on simulated soil environmental conditions and series of biochemical and geochemical reactions determining the transport and transformation of C and N components. To allow simultaneous occurrence of nitrification and denitrification in aerobic or anaerobic microsites, the scheme of a dynamic ‘anaerobic balloon’ is applied, which is based on the availability of O$_2$ in the respective soil layer and allocates substrates such as DOC, NH$_4$ and NO$_3$ into aerobic and anaerobic soil compartments. DNDC models have been developed for site application but are also used in combination with GIS for quantification of atmosphere-biosphere-hydrosphere matter exchange on regional, national and global scales.

**Century model**

The CENTURY model is a generalized plant-soil ecosystem model that simulates plant production, soil carbon dynamics, soil nutrient dynamics, and soil water and temperature. The model has been used to simulate ecosystem dynamics for all of the major ecosystems in the world and has been used for the dominant cropland and agroecosystems. The model results have been compared to observed plant production, soil carbon, and soil nutrient data for the most common global natural and managed ecosystems. The model has been used to simulate the response of these ecosystems to changes in environmental driving variables (i.e. maximum and minimum air temperature, precipitation and atmospheric CO$_2$ levels) and changes in the management practices (grazing intensity, forest clearing practices, burning frequency, fertilizer rates, crop cultivation practices, etc.) for grasslands, crop, forest and savanna ecosystems. The Century model (Parton et al., 1987, 1993) is one of the more widely-used ecosystem carbon models. Several applications have been done in Europe using data from long term experiments in Sweden (Paustian et al., 1992), Italy (Lugato et al., 2007) and in Germany, UK and Czech Republic (Kelly et al., 1997), also in comparison with other SOC models (Smith et al., 1997).

**RothC model**

RothC is a soil organic carbon model that accounts for the effect of soil type, temperature, moisture content and plant cover on the turnover of organic carbon in soils. It is originally developed and parameterized to model the turnover of organic carbon in arable top soils from the Rothamsted long term field experiments and is basically concerned with soil processes. It uses a
monthly time step to calculate total organic carbon (t ha$^{-1}$), microbial biomass carbon (t ha$^{-1}$) and Δ14C (from which the equivalent radiocarbon age of the soil can be calculated) on a ‘years to centuries’ timescale (Jenkinson et al., 1987; Jenkinson et al., 1992; Jenkinson and Coleman, 1994). RothC is designed to run in two modes: ‘forward’ in which known inputs are used to calculate changes in soil organic matter and ‘inverse’, when inputs are calculated from known changes in soil organic matter. Soil organic carbon is split into four active compartments and a small amount of inert organic matter (IOM). The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition. The structure of the model is shown in figure 1. Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For most agricultural crops and improved grasslands, the model uses a DPM/RPM ratio of 1.44, i.e. 59% of the plant material is DPM and 41% is RPM. For unimproved grassland and scrub (including Savanna) a ratio of 0.67 is used. For deciduous or tropical woodland a DPM/RPM ratio of 0.25 is used, so 20% is DPM and 80% is RPM. All incoming plant material passes through these two compartments only once. Both DPM and RPM decompose to form CO$_2$, BIO and HUM. The proportion that goes to CO$_2$ and to BIO + HUM is determined by the clay content of the soil. The BIO + HUM is then split into 46% BIO and 54% HUM. BIO and HUM both decompose to form more CO$_2$, BIO and HUM. RothC-26.3 is tested in long term experiments on a range of soils and climatic conditions in Western and Central Europe. In a majority of cases, this model was tested on long-term experimental sites with detailed descriptions of the sites conditions and treatments (Coleman et al., 1997; Smith et al., 1997; Falloon and Smith, 2002; Barancikova 2007; Ludwig et al., 2007). Because of its simplicity and the generally good availability of the input data required, this model is used also for the estimation of the SOC stock on agricultural land.

**Review on use of different SOM models in India**

SOM models have been widely used internationally. Table 2 summarizes the use of different SOM models in predicting SOM dynamics in different agroecosystems of India. Bhattacharyya et al. (2011) evaluated RothC model in four long term fertilizer experimental sites representing subhumid moist (Sarol and Nabibagh), sub-humid dry (Panjri) and semi-arid (Teligi) climate in India. The model performance was found to be good to simulate changes in soil organic carbon on typical black soils. They further reported that the model simulates the observation that inorganic fertilizers alone did not increase total organic carbon, while the combination of inorganic and organic does so; in both the events however crop yields are increased. Bhattacharyya et al. (2010) also evaluated the century model in two long-term fertilizer experiments (LTFE) datasets were used to evaluate the performance of the Century ecosystem model in contrasting regions of India viz Mohanpur (humid) and Akola (semi-arid) with mean annual rainfall of 1619mm and 793mm, respectively. Mohanpur grew rice and wheat in rotation for 19 years since 1986. Akola grew sorghum and wheat in rotation for 9 years since 1988. The model closely resembled measured SOC level for all the treatments with different doses of inorganic (fertilizer) and organic (farm yard manure, paddy straw, and green manure) inputs in Mohanpur LTFE. However at the semi-arid site Century performed well for the early years, but lower during the end of the experiment. Bhattacharyya et al. (2007) modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains of India using GEFSOC modelling System (Global Environment Facility co-financed Soil Organic Carbon). The predicted SOC stocks and changes for IGP region using GEFSOC modelling System was compared against stocks generated using mapping approaches based on soil survey data. The SOC stock estimated using the GEFSOC Modelling System is higher than the stock estimated using the mapping approach. This is due to
the fact that while the GEFSOC System accounts for variation in crop input data (crop management), the soil mapping approach only considers regional variation in soil texture and wetness.

**Conclusion:**

The potential of soil to act as sink for atmospheric carbon has emphasized the importance of soil carbon accumulation and sequestration. Soil organic carbon is essential and imperative for all essential soil functions and processes (physical chemical and biological). The turnover of soil organic matter and its dynamics plays a pivotal role in soil carbon sequestration and stabilization. Management of agricultural land is an integral part of the global terrestrial carbon pool including carbon cycle. Several management practices (for e.g., agro-forestry, soil management, biochar and reduce land clearing) including land use land use change and forestry have been shown to increase soil carbon. This whole soil ecosystem along with soil organic matter is very complex process to understand. Soil organic matter models help studying the effect of management practices on soil organic matter turnover and dynamics. Models are important tools to understand any complex biological process in a simplified and easy way. The review also indicates that soil organic matter models viz., Century and RothC are widely used model to simulate the management effects in the different bio-climatic systems in terms of predicting SOC change. SOM models also help in developing inventory of soil carbon at regional and national level which could serve as ready reckoned in calculating the carbon credits. Thus SOM models could serve as promising tools in prediction of soil organic carbon stock as a consequence of climatic changes and rapid changes in the land use and land management in the future.

**References**


Introduction
India is predominantly an agrarian economy both from the point of view of employment as well as contribution to the national income. Availability of reliable and timely agricultural statistics is hence of paramount importance to the planners, administrators, policy makers and research scholars. Government depends on these data in taking policy decisions regarding production, pricing, processing, procurement, storage, transport, marketing, export/import, public distribution and many other related issues including investment planning. A continuous evaluation of the mechanism for generation of timely and reliable agricultural statistics, therefore assumes special significance.

The Directorate of Economics & Statistics in the Department of Agriculture & Cooperation is the nodal official agency for collection, compilation and publication of major agricultural statistics like area and production estimates of principal crops. From the point of view of collection of area statistics, the states in the country are divided into three broad categories:

States and Union Territories, which has been cadastral surveyed, and where area and land use statistics of built up are a part of the land records maintained by the revenue agencies (referred to as “Land Records States” or temporary settled states). The system of land records is being followed in major states and 4 Union territories of Chandigarh, Delhi, Dadar & Nagar haveli and Pondicherry. These states/Union territories accounts for about 86% of reporting area.

The states where area statistics are collected on the basis of sample surveys (normally known as non-land record states or “Permanently Settled States” which are three in number viz. Kerala, Orissa and West Bengal). A scheme for Establishment of Agency for Reporting of Agricultural Statistics (EARAS) has been introduced in these three states which envisages, inter-alia, either the estimation of areas by complete enumeration or through sample surveys in a sufficiently large sample of 20% villages/investigators zone. These states accounts for about 9% of reporting area.

In the hilly districts of Assam, the rest of the states in North-Eastern Region, Sikkim, Goa, Union territories of Andaman Islands, Daman & Diu and Lakshwadeep where no reporting agency had been functioning, the work of collection of Agricultural Statistics is entrusted to the village headman of the reporting area (5%).

The area statistics are collected on complete enumeration basis in some of the states falling under category (1) and a scheme for Establishment of Agency for Reporting of Agricultural Statistics (EARAS) has been introduced in the three states in category (2). While in category (3) the area statistics are collected on the basis of ad-hoc methods based on impressionistic approach from the village headman which are purely unscientific and non-statistical. The estimates of area under different crops are given on the basis of eye estimation only. These figures are not based on any scientific basis and hence may not be accurate and reliable. Therefore, there is need to develop a scientific methodology with strong statistical background which is capable of providing reliable estimates of area under different crops in these regions.

With the advent of Remote Sensing technology during seventies and its great potential in the field of agriculture have opened new vistas of improving the agricultural system all over the world. The remote sensing techniques to obtain the land utilization statistics gained popularity because of its extensive coverage of geographical area. It is therefore required to explore the possibility of use of satellite Remote Sensing for collecting agricultural statistics on a regular basis. The recent advances in the field of geographical techniques, like Geographic Information System (GIS) increased the potential to change substantially the statistical approach to study the geographical
realities. GIS, is capable of handling geographical data obtained by different sources like Census, Survey and Remote Sensing.

There is no objective methodology for estimation of area under different crops in North-Eastern states due to the typical problems existing in these regions. The North-eastern states particularly Meghalaya, mainly consists of hilly region with thick forest cover. Besides this, the main problem is its undulating topography and non-accessibility of vast area. Further, the relative percentage area under the crops is very less. Mostly terraced farming and Jhum cultivation is practiced in these regions. Moreover, these areas particularly Meghalaya, are covered by clouds most of the time. Thus it is difficult to get cloud free images of these areas. Therefore, use of remote sensing satellite data alone may not be able to provide reliable information. There are no cadastral maps and village boundary maps existing for these regions. The exact information regarding total number of villages in each district/block is also not available. Further, within a village’s total number of farmers, number of fields owned by each farmer, crops grown by the framers etc. is also not known. Thus, the traditional methodology of area estimation is also not applicable in these regions.

Keeping all this in view, it was considered that the use of satellite data along with the ground survey data in GIS environment may be useful to obtain the reliable estimates for the area under crops. In absence of any satisfactory objective technique for this situation, this study has been divided in two phases. In the first stage, field problems have been studied by conducting a pilot study at district level. The basic aim of the pilot study was to develop a suitable survey methodology for estimation of area of paddy crop in one district of Meghalaya. For this Ri-Bhoi, which is considered to be the Rice Bowl of Meghalaya, has been selected. In the second phase, to validate the methodology developed during the pilot study, it has been repeated in the same district and also applied in one more district of the state in order to estimate the area under paddy crop. Further an attempt has also been made to develop methodology for estimation of area under multiple crops like Paddy, Ginger, Maize, Pineapple, Potato Cashewnut, Vegetables which is given in the subsequent sections.

Methodology for estimation of area under paddy in hilly regions:
Two approaches have been followed to obtain the area under paddy in the district.

1. Village Survey Approach
2. An integrated approach based on Remote Sensing, GIS along with survey data.

Village Survey Approach
The village survey approach for estimation of area under crop is followed in those states, which are permanently settled such as Kerala, West Bengal and Orissa. Similar approach was adopted here for estimation of area under paddy in the study district. In this approach 20 villages were selected through simple random sampling without replacement from the available sampling frame of the villages in the district. The list of all the farmers growing paddy crop in the village has been prepared on the basis of information collected from the village headman in the selected villages. A sample of 5 farmers has been selected from each village from the sampling frame of paddy growing farmers. The area under paddy in the farmer’s paddy fields has been recorded by enquiry from the selected farmers. Out of these farmers, 2 farmers were randomly selected for recording area of each of their paddy fields through GPS.

Numbers of problems have been faced during the implementation of this approach. In this state, system of land records does not exist and the village headman decides its ownership for a particular period of time. Therefore, the area of the fields is not measured and farmer-growing crop on a particular field does not have much idea about the area of the field. It has been found that area
of the field reported by the farmer and area of the same field as observed by GPS has no relationship. This also holds true for the area figures reported by the village headman. The $R^2$ of linear relationship between actual area of the field as observed by GPS and area of the field as reported by the farmers is very low i.e., 0.07. Further, there is no concept of village boundaries existing in the state in a strict sense. Therefore, the exact figure for total numbers of villages in the district is not known as different agencies are reporting different figures. Similarly, the nature and size of the villages also differs. The villages, which are approachable, are of relatively bigger size and more uniform as compared to villages, which are away from roads. Further, paddy crop is generally grown in the villages, which are in the valleys or low laying areas. Therefore, estimation of paddy area based on total number of villages in the district is always likely to provide over estimation of area, as the list of paddy growing villages are not available. Keeping in view above points, this approach was not found to be feasible and it is recommended that this should not be adopted in future.

**Integrated approach using Remote Sensing and GIS along with Survey data**

The traditional methodology of crop area estimation may it be complete enumeration or sample survey conducted in other parts of the country is not applicable in Meghalaya as no land record system is existing in the state, there are no cadastral maps and village boundary maps available. The exact information regarding total number of villages in each district/block is also not available. Further, within a village’s total number of farmers, number of fields owned by each farmer, crops grown by the framers etc. is also not known. Next if one thinks of applying remote sensing tool for crop area estimation, which is very successful in the plains, some other problem arises like thick forest cover, undulating topography, non-accessibility of vast area, terraced farming and Jhum cultivation which makes direct application of satellite data difficult for crop area estimation. Moreover, these areas particularly Meghalaya, is covered by clouds most of the time during the year which makes it difficult to get cloud free images of these areas. Therefore, use of remote sensing satellite data alone is also not capable of providing reliable information regarding area under different crops. Keeping all this in view, it was considered that the use of satellite data along with the ground survey data in GIS environment may be useful to obtain the reliable estimates for the area under crops. Thus, an integrated approach using remote sensing, extensive ground survey and GIS is developed to estimate area under paddy crop. The field problems has been identified and grouped into three major categories and efforts have been made to resolve these problems in this approach.

The three groups of problems identified for crop area estimation using remote sensing data are the following:

(i) Due to undulating topography of the region, misclassification and angle of the sensor there may be significant differences of area under crop in the image and actual area under crop on the ground, which may result in larger extent of misclassification errors.

(ii) The area under paddy crop falling under hill shades or valleys, which may not be exposed, to the satellite sensor, as satellite sensors are sun-synchronous. Further, small paddy fields are not detectable due to lower spatial resolution of the LISS-III sensors.

(iii) Cloud cover in the satellite image.

The solution for each of these problems is suggested below which forms the part of our methodology. In order to rectify the area under paddy crop due to undulating topography and misclassification errors, a relationship between area under paddy in the classified image and actual area under paddy crop on the ground has been established. The area under paddy, which has not been captured by satellite sensor due to hill shades and limitations of spatial resolution of the sensor, has been rectified by a suitable sample survey in the buffer created along selected roads in GIS environment. Suitable estimator has been then developed to estimate the area under paddy
crop in this buffer zone. The vector layer of this buffer was overlaid on the classified image and the corresponding area from the image was extracted. For cloud removal initially composite technique has been applied. Besides this some other estimators are also developed for estimating paddy area under clouds or cloud shadow. Using these estimates, an improved estimate of area under paddy in the entire district was obtained. The entire methodology developed and applied is shown in Figure 2.1. The detailed steps followed under this approach are given in the following sections.

**Estimation of area under paddy by digital classification**

For estimation of area under a crop choice of the satellite data pertaining to some specific period in which that crop can be easily identified is very important. In Meghalaya, the winter paddy period extends from August-September to December-January. Field observation with satellite imagery shows that in these areas, there may be two critical period for choosing the satellite data for delineation of paddy areas. During the early vegetative growth period, because of thin canopy density and visible underneath water gives a typical signature. This signature helps in delineating paddy area from nearby grassland or forestland, which gives very bright red signature because of healthy vegetation in the monsoon/post monsoon season. As per the crop calendar, the September month will be ideal for acquiring satellite image for winter paddy. The September image for delineation of paddy is advisable as during this period paddy field was in the puddling and transplanting stage, thereby giving a unique spectral signature which could be easily separated from rest of the neighboring land cover classes specially other crops grown during that period. If paddy which is cultivated in wet condition is the only crop grown in this period, any chances of misinterpretation because of other crop grown in wet condition are also eliminated. A second time period will be where paddy crop will be in mature stage. During this time image will give typical signature, which will allow delineating paddy crop from nearby vegetation. Images acquiring during the month of November will be ideal for this purpose. It is observed that in the month of December and January in the areas with barren hills vegetation cover used to dry up and signature mixed with harvested paddy field. In this period it will be difficult to delineate the paddy area from nearby neighboring vegetation cover. Maximum likelihood classifier was found to be accurate enough for classifying the study area for extraction of paddy fields.

**Estimation of area under cloud**

Cloud cover is a very complex problem in optical remote sensing especially over the humid tropical regions. One of the most common solutions to this problem is to produce a cloud free mosaic from several multi-date images acquired over the same area of interest. In this method the image containing the least cloud cover is taken as the base image. The cloudy areas in the image are masked out, and then filled in by the cloud free areas from other images acquired at different time. This is known as compositing technique for cloud removal. This is a very crude method of cloud removal. Moreover for this we need cloud free data of the recent past and of the same time period. The cloud free data of recent past may not always be available especially in places like Meghalaya and since clouds follows a random pattern so the clouds will appear at different places in different time period. So it is always not possible to get the past data of same time period. In order to get rid of this difficulty, two other techniques for estimating the exact paddy area or number of paddy pixels under cloud cover present in the satellite imagery has been developed based on the previous area data as well as on the basis of current year data. These techniques are described in detail in the following sections:

**Estimation of area under cloud using Compositing technique**

Under this approach, data for two different years has been classified. One is the current year data containing clouds and another is the data for past year, which is cloud free. Then the area or patches, which are containing clouds/ cloud shadow in the current year image are substituted with
the patches obtained from cloud free image of past year. We may take the data of previous year, as the past year data as generally there is not much change in the area under crops.

**Estimation of paddy area under cloud using previous year data as auxiliary variable**

Let the total number of paddy pixels in the image of 2005 be denoted by $Z_p$. Let the total number of paddy pixels in the image of year 2002 be denoted by $U_p$. Let the number of paddy pixels in the image of year 2002 excluding the pixel under cloud cover/ cloud shadow in the image of 2005 be denoted by $u_p$. Then applying the usual ratio estimator for total (Cochran, 1940) the estimate of total number of paddy pixels in 2005 will be obtained as follows:

$$\hat{Z}_p = \frac{Z_p}{u_p} U_p$$

This will give the estimate of total paddy pixels in the current year image from which the total area under paddy can easily be calculated. For calculation of total number of paddy pixels in the image of previous year, current year and paddy pixels in the image of previous year excluding the pixel under cloud cover/ cloud shadow in the current year image algorithms were complied in C language.

**Estimation of area under cloud on the basis of current year data only**

The drawback of the above mentioned two methods for accounting for the cloud area is that if we do not get cloud free image of recent past and also the data for the same period these methods cannot be applied. In that case we are suggesting an alternative methodology, which is based only on the basis of current year data. Under this method a grid of 5*5 km is overlaid on the entire image of the study area. The grids covering the whole image is then divided into strata on the basis of percentage of area covered under cloud or cloud shadow in the following manner:

- **Strata I**: Grids not containing any area under cloud/ cloud shadow
- **Strata II**: Grids covering less than 10% of area under cloud/ cloud shadow
- **Strata III**: Grids covering 10% to 25 % of area under cloud/ cloud shadow
- **Strata IV**: Grids covering 25 % to 50 % of area under cloud/ cloud shadow
- **Strata V**: Grids covering more than 50% of area under cloud/ cloud shadow

Let the total geographical area of the $t^{th}$ stratum be denoted by $Y_{gt}$, let the area under paddy of the $t^{th}$ stratum as obtained by classified image be represented by $Y_{pt}$. Let the area under cloud/ cloud shadow of the $t^{th}$ stratum be represented by $Y_{ct}$. Then the total cloud/ cloud shadow free geographical area of the $t^{th}$ stratum denoted by $(Y_{gt}^*)$ can be computed as:

$$Y_{gt}^* = Y_{gt} - Y_{ct}$$

The total paddy area under cloud/ cloud shadow for the $t^{th}$ stratum can be estimated as
Therefore total area under paddy in the $t^{th}$ stratum ($Y_{pt}^{*}$) can be obtained as

$$Y_{pt}^{*} = \frac{Y_{pt}}{Y_{gt}}$$

Now it is easy to estimate the total area of the district as obtained by classified image after estimating the area under cloud and cloud shadow ($Y_{pd}$)

$$Y_{pd} = \sum_{i=1}^{5} Y_{pt}^{*}$$

$Y_{pd}$ gives the estimate of total paddy area in the district as obtained by classified image after making correction for the area covered by cloud and cloud shadow.

**Development of relationship between area under paddy crop in the image and actual area under paddy on the ground**

To develop a relationship between area under paddy in the image and actual area under paddy on the ground a suitable number of paddy patches/fields, which are clearly visible and de-markable in the FCC of the study area have been identified. The actual area of these patches/fields was recorded on the ground by using a Global Positioning System (GPS). Further, these patches were extracted from the classified digital image and the corresponding area under paddy was recorded.

Let there be ‘$n_r$’ clearly visible paddy patches/fields, which can be demarcated in the FCC as well as on the ground. Let $Y_{(r)i}$ and $X_{(r)i}$ denote the area under paddy crop as obtained by GPS on the ground and from the classified image for $i^{th}$ paddy patch respectively. The model can represent the linear relationship between area measured by GPS and obtained by classified image:

$$Y_{(r)i} = a_{(r)i} + \beta_{(r)i} X_{(r)i} + e_{(r)i}$$

$$i = 1,2,3,...,n_r$$

Using the above model, the area under paddy crop obtained from the classified satellite image can be considerably corrected for undulating topography, miss-classification errors and angle of sensor.

**Estimation of paddy area in the buffer zone through ground survey**

In order to estimate the extent of area under hill shades and non-visible area due to smaller paddy fields (limitation of spatial resolution of satellite sensors) a field survey was conducted. Conducting a field survey in this region has several limitations such as highly undulating topography, inaccessibility of most of the area etc. Keeping in view the above factors it was decided to conduct this survey along the major roads of the district. Further, it has been observed that cultivation of paddy along the road is one of the dominant land use in this district.

**Field survey and data collection**
A buffer zone of 250 meters was created along the roads in GIS environment, which has been considered for conducting the survey. The roads of the district were divided into three categories: (i) National Highway, (ii) Primary roads and (iii) Secondary roads. Some of the roads from each category were taken for this survey. Each of these roads was further divided into segments of 500-meter length on the buffer zone of 250 meter on both sides of the road thus getting a square grid of 500*500 m². In each of the selected grids of 500 X 500 m² area under paddy crop in each field has been recorded through eye estimates. Further, actual area under paddy crop was measured using GPS for accessible grids only. The schedules have been designed for the data collection. The instruction manuals for proper understanding of schedules and how to fill up the schedules have also been prepared.

Development of a linear relationship between area under paddy through eye estimate and actual measurement taken through GPS

Let \( Y_{(be)hji} \) denotes the area under paddy in \( i^{th} \) grid of \( j^{th} \) road from \( h^{th} \) category as recorded by eye estimate. Similarly, \( Y_{(bg)hji} \) denotes the area under paddy crop in \( i^{th} \) grid of \( j^{th} \) road from \( h^{th} \) category as measured by GPS, where \( i=1, 2, 3... \ m_{bg} \) and \( m_{bg} \leq m_{bh} \) as the area under paddy has been recorded only for approachable grids. The area under paddy through eye estimate from those segments, where it was not measured by GPS was corrected by following equation.

\[
\hat{y}_{(bg)hji} = \hat{\alpha}_{(b)} + \hat{\beta} * Y_{(be)hji(b)} \quad \text{…… (2)}
\]

Estimate of area under paddy in the buffer zone

The estimate of area under paddy can be obtained on the basis of all the surveyed grids and also on the basis of grids containing paddy area only.

Let \( \hat{Y}_{(b)} \) denotes the estimate of total area under paddy in the buffer zone which is given as:

\[
\hat{Y}_{(b)} = \sum_{h=1}^{1} \sum_{j=1}^{N_{bh}} \sum_{i=1}^{m_{bh} \leq m_{bg}} \frac{M_{(b)hj}}{m_{(b)hj}} \sum_{i=1}^{m_{hji}} Y_{(bg)hji}
\]

Improved estimate of total area under paddy in the district

The total area under paddy in the district is estimated by correcting for the non-detectable area under paddy obtained through remote sensing and the field survey estimator in the buffer zone along the roads.

Let \( \hat{Y}_p \) be the total area under paddy in the district. Let \( \hat{Y}_{(c)} \) denotes the area under paddy in the district as obtained by the classified image. Further, let \( \hat{Y}_{(b)} \) is the area under paddy in the buffer zone as estimated by the road survey and \( \hat{Y}_{(br)} \) be the corresponding area as obtained through the classified satellite image. Then the improved estimate of crop area under paddy in the district as given by,
\[
\hat{Y}_p = \frac{\hat{Y}_{(b)}}{\hat{Y}_{(br)}} \hat{Y}_{(t)} \quad \ldots \ldots(3)
\]

Methodology for estimation of area under multiple crops in hilly regions:

The methodology developed for multiple crop acreage estimation is as follows:

**Sampling Design**

Spatial stratification has been done using cropped area layer which was extracted from land use/land cover maps and was categorized as LOW, MEDIUM and HIGH on the basis of cropped area and digital elevation model (DEM) layer which was categorized as LOW, MEDIUM and HIGH on the basis of elevation. The two layers were overlaid to form nine strata which are (i) High Cultivation High Elevation (HCHE) (ii) High Cultivation Moderate Elevation (HCME) (iii) High Cultivation Low Elevation (HCLE) (iv) Moderate Cultivation High Elevation (MCHE) (v) Moderate Cultivation Moderate Elevation (MCME) (vi) Moderate Cultivation Low Elevation (MCLE) (vii) Low Cultivation High Elevation (LCHE) (viii) Low Cultivation Moderate Elevation (LCME) (ix) Low Cultivation Low Elevation (LCLE). Sixty villages/ Habitats were selected from each district from the selected strata by proportional allocation. Five farmers were selected from each of these selected villages/habitats. Data was collected from these selected farmers for variables such as general information of the habitat, Crops grown in current season in the habitat, their average seed rate, sowing month, harvesting month, average yield, expected Production, and area of each field by eye estimate and by measurement.

**Estimation Procedure**

The estimation procedure developed to obtain the estimates of area under a particular crop in a district is given below:

Let \( \hat{A}_{cd} \) be the estimated area under a crop C in the district which is given by
\[
\hat{A}_{cd} = \hat{P}_c \times A_R
\]
where \( A_R \) is the total estimated cropped area obtained by satellite imagery in the district for current season
and
\[
\hat{P}_c = \sum W_h \hat{P}_{ch}
\]
where \( W_h = \frac{A_h}{A} \) \( A_h \) being the cropped area of the \( h^{th} \) stratum obtained from Land use / Land cover map and \( A \) being the cropped area of the district obtained from Land use / Land cover map.

\( \hat{P}_{ch} = \) Area under crop C in the \( h^{th} \) stratum / Total cropped area of \( h^{th} \) stratum

**Conclusions**

The methodology developed for the estimation of area under paddy crop is widely accepted and is extended for other districts of the state. It has become operational for the entire state of Meghalaya.
The methodology will also be extended to other North-eastern states like Manipur and Mizoram. The methodology for the acreage estimation for multiple crops is still in development stage and research is going on in this direction.

References:


Introduction

Spatial data analysis aims at extracting implicit knowledge such as spatial relations and patterns that is not explicitly stored in spatial databases. It distinguishes itself from classical data analysis in that it associates with each object the attributes under consideration including both non-spatial and spatial attributes.

We distinguish three prevalent spatial data types, defined by the topology of the entity to which the recorded information refers. These are point, lines and area. Features having a specific location, but without extent in any direction are considered as points. A pair of coordinates represents a point. Village locations, industrial locations, cities etc. are the examples of the point data. Lines features consist of series of x, y coordinate pairs with discrete beginning and ending points. Features like rivers, road networks, represents lines. Features defined by a set of linked lines enclosing an area are known as polygons. Polygons are characterized by area and perimeter. Administrative boundaries, land use, soil map etc. are the polygon features.

Statistical analysis which deals with spatial data is termed as the science of Spatial statistics. Spatial statistics span many disciplines, with methods varying in relation to the specific research questions being addressed, whether predicting ore quality in mining, examining suspiciously high frequencies of disease events, or handling the vast data volumes being generated by GPS (global positioning system) and satellite remote sensing. A unique feature of spatial data is that geographical location provides a key shared either exactly or approximately between data sets of different origins. Census data can be overlayed over patient or customer data; environmental data can be integrated with disease frequencies; problems which hitherto did not admit ready empirical testing are becoming approachable. It is an area of spatial analysis that has grown significantly in the last twenty years. It encompasses an impressive array of sophisticated methods and techniques for visualization, exploration and modeling of spatial data which are described here.

Descriptive Spatial Statistics

A set of descriptive spatial statistics has been developed (Table 1) that are areal or locational equivalents to the nonspatial measures.

Table 1: Nonspatial and Spatial Descriptive Statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Central tendency</th>
<th>Absolute Dispersion</th>
<th>Relative Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonspatial Spatial</td>
<td>Mean</td>
<td>Standard Deviation</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td></td>
<td>Mean Center or Median Center or Euclidean Median</td>
<td>Standard Distance</td>
<td>Relative Distance</td>
</tr>
</tbody>
</table>

Spatial Measures of Central Tendency

Mean Center

The mean is an important measure of central tendency for a set of data. If this concept of central tendency is extended to locational point data in two dimensions (X and Y coordinates), the average location, called the mean centre, can be determined.
Consider the spatial distribution of points shown in Fig. 1. These points might represent any spatial distribution of interest, the only stipulation is that the phenomenon can be displayed graphically as a set of points in a two-dimensional coordinates system.

Once a coordinate system has been established and the coordinates of each point determined, the mean center can be calculated by separately averaging the X and Y coordinates, as follows:

\[
\bar{X}_c = \frac{\sum X_i}{n} \quad \text{and} \quad \bar{Y}_c = \frac{\sum Y_i}{n}
\]

where

- \( \bar{X}_c \) = mean center of \( X \), \( \bar{Y}_c \) = mean center of \( Y \)
- \( X_i \) = X coordinate of point \( i \), \( Y_i \) = Y coordinate of point \( i \)
- \( n \) = number of points in the distribution

For the point pattern shown in Fig. 1, the mean centre coordinates are \( \bar{X}_c = 3.81 \) and \( \bar{Y}_c = 2.51 \).

The mean center may be considered the center of gravity of a point pattern or spatial distribution. In many geographic applications, it is appropriate to assign differential weights to points in a spatial distribution. The weights are analogous to frequencies in the analysis of grouped data (e.g., weighted mean).

\[
\bar{X}_{wc} = \frac{\sum f_i X_i}{\sum f_i} \quad \text{and} \quad \bar{Y}_{wc} = \frac{\sum f_i Y_i}{\sum f_i}
\]

- \( \bar{X}_{wc} \) = weighted mean center of \( X \)
- \( \bar{Y}_{wc} \) = weighted mean center of \( Y \)
- \( f_i \) = frequency (weight) of point \( i \)

The mean center serves as a spatial analogue to the mean, in that it is the location that minimizes the sum of squared deviations of a set of points. Thus, the mean center has the same least squares property as the mean. The mean center \((\bar{X}_c, \bar{Y}_c)\) minimizes:
\[ \sum [(X_i - \overline{X}_c)^2 + (Y_i - \overline{Y}_c)^2] \]

In a location coordinate system, deviations such as \((X_i - \overline{X}_c)\) and \((Y_i - \overline{Y}_c)\) are, in fact, distances between points. One standard procedure for measuring distances is based on straight line or Euclidean distance. The Euclidean distance \(d_i\) separating point \(i\) \((X_i, Y_i)\) from the mean center \((\overline{X}_c, \overline{Y}_c)\) is defined by the Pythagorean theorem as follows:

\[ d_i = \sqrt{(X_i - \overline{X}_c)^2 + (Y_i - \overline{Y}_c)^2} \]

Thus, the mean center is the location that minimizes the sum of squared distances to all points. This characteristic makes the mean center an appropriate center of gravity for a two-dimensional point pattern, just as the mean is the center of gravity along a one-dimensional number line.

**Euclidean Median**

For many geographic applications, another measure of “center” is more useful. Often, it is more practical to determine the central location that minimizes the sum of unsquared, rather than squared, distances. This location, which minimizes the sum of Euclidean distances from all other points in a spatial distribution to that central location, is called the Euclidean median \((X_e, Y_e)\) or median center. Mathematically, this location minimizes the sum:

\[ \sum \sqrt{(X_i - X_e)^2 + (Y_i - Y_e)^2} \]

Determining coordinates of the Euclidean median is complex methodologically. A weighted Euclidean median is a logical extension of the simple (unweighted) Euclidean median. The coordinates of the weighted Euclidean median \((X_{we}, Y_{we})\) will minimize the expression

\[ \sum f_i \sqrt{(X_i - X_{we})^2 + (Y_i - Y_{we})^2} \]

The weights or frequencies may represent population, sales volume, or any other feature appropriate to the spatial problem.

**Spatial Measures of Dispersion**

**Standard Distance**

As the mean center serves as a locational analogue to the mean, standard distance is the spatial equivalent of standard deviation. Standard distance measures the amount of absolute dispersion in a point pattern. After the locational coordinates of the mean center have been determined, the standard distance statistic incorporates the straight-line or Euclidean distance of each point from the mean center. Standard distance \((S_D)\) is written as follows:

\[ S_D = \sqrt{\frac{\sum (X_i - \overline{X}_c)^2 + \sum (Y_i - \overline{Y}_c)^2}{n}} \]
or \[ S_D = \sqrt{\left( \frac{\sum X_i^2}{n} - \overline{X}_c^2 \right) + \left( \frac{\sum Y_i^2}{n} - \overline{Y}_c^2 \right)} \]

Like standard deviation, standard distance is strongly influenced by extreme or peripheral locations. Because distances about the mean center are squared, “uncentered” or atypical points have a dominating impact on the magnitude of the standard distance. The standard distance is calculated in Table 2 and shown as the radius of a circle whose centre is the mean center in Fig.2. Weighted standard distance is appropriate for those geographic applications requiring a weighted mean center. The definitional formula for weighted standard distance \( S_{WD} \) is:

\[ S_{WD} = \sqrt{\frac{\sum f_i (X_i - \overline{X}_c)^2 + \sum f_i (Y_i - \overline{Y}_c)^2}{n}} \]

**Table 2: Table for Calculating Standard Distance**

<table>
<thead>
<tr>
<th>Point</th>
<th>Locational Coordinates</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( X_i )</td>
<td>( Y_i )</td>
<td>( X_i^2 )</td>
<td>( Y_i^2 )</td>
</tr>
<tr>
<td>A</td>
<td>2.8</td>
<td>1.5</td>
<td>7.84</td>
<td>2.25</td>
</tr>
<tr>
<td>B</td>
<td>1.6</td>
<td>3.8</td>
<td>2.56</td>
<td>14.44</td>
</tr>
<tr>
<td>C</td>
<td>3.5</td>
<td>3.3</td>
<td>12.25</td>
<td>10.89</td>
</tr>
<tr>
<td>D</td>
<td>4.4</td>
<td>2.0</td>
<td>19.36</td>
<td>4.00</td>
</tr>
<tr>
<td>E</td>
<td>4.3</td>
<td>1.1</td>
<td>18.49</td>
<td>1.21</td>
</tr>
<tr>
<td>F</td>
<td>5.2</td>
<td>2.4</td>
<td>27.04</td>
<td>5.76</td>
</tr>
<tr>
<td>G</td>
<td>4.9</td>
<td>3.5</td>
<td>24.01</td>
<td>12.25</td>
</tr>
</tbody>
</table>

\( \overline{X}_c = 3.81 \) and \( \overline{Y}_c = 2.51 \), \( \overline{X}_c^2 = 14.52 \) and \( \overline{Y}_c^2 = 6.30 \), therefore \( S_D = 1.54 \).
Relative Distance

The coefficient of variation (standard deviation divided by the mean) is the nonspatial measure of relative dispersion. A perfect spatial analogue to the coefficient of variation does not exist for measuring relative dispersion.

To derive a descriptive measure of relative spatial dispersion, the standard distance of a point pattern is divided by some measure of regional magnitude. One possible divisor is the radius \( r_A \) of a circle with the same area as the region being analyzed. A useful measure of relative dispersion, called relative distance \( R_D \), can now be defined:

\[
R_D = \frac{S_D}{r_A}
\]

This relative distance measure allows direct comparison of the dispersion of different point patterns from different areas, even if the areas are of varying sizes.

SPATIAL ASSOCIATION

Spatial association enables to assess statistically the degree of spatial dependence in the data. Finding the degree of spatial association (correlation) among data representing related locations is fundamental to the statistical analysis of dependence and heterogeneity in spatial patterns. In 1960s the most challenging spatial question was: In an unbiased way, how is one to account for the correlation in spatially distributed variables? The next problem was the difficulty in dealing with unequally sized and irregularly shaped units.

Chi-Square Statistic

The Chi-Square statistic measures the strength of association between spatial distributions of two variables. For example relationship between wheat yield and precipitation or relation between two maps showing high and low yields and high and low precipitation.

Spatial Autocorrelation

Given a group of mutually exclusive units or individuals in a two dimensional plane, if the presence, absence or degree of a certain characteristic affects the presence, absence or degree of the same characteristic in neighbouring units, then the phenomenon is said to exhibit spatial autocorrelation (Cliff and Ord, 1973). Spatial autocorrelation tests whether or not the observed value of a variable at one locality is independent of values of that variable at neighbouring localities. A positive spatial autocorrelation refers to a map pattern where geographic features of similar value tend to cluster on a map, whereas a negative spatial autocorrelation indicates a map pattern in which geographic units of similar values scatter throughout the map. When no statistically significant spatial autocorrelation exists, the pattern of spatial distribution is considered to be random (Figure).

Classical Measure of Spatial Autocorrelation

- Moran’s I
- Geary’s C
Moran (1950) proposed the following measure to calculate the spatial autocorrelation ($\beta$):

$$\beta = \frac{N}{S} \sum_{i=1}^{N} \sum_{j=1}^{N} W_{ij} (x_i - \bar{x})(x_j - \bar{x})$$

$$S = \sum_{i=1}^{N} \sum_{j=1}^{N} W_{ij} , \quad (i \neq j)$$

Where, $x_i$ is the observed value at location $i$, $N$ is the number of locations and. The weighting function $w_{ij}$ is used to assign weights to every pair of locations in the study area.

$$w_{ij} = 1 , \quad \text{if } i \text{ and } j \text{ are neighbours and } = 0 , \quad \text{otherwise}$$

The range of Moran’s autocorrelation varies from approximately -1 to +1. Positive sign represents positive spatial autocorrelation, while the converse is true for negative. Zero indicates no spatial autocorrelation. For calculation of weighing function one needs to identify whether the two locations are neighbours or not. This requires the criteria to decide about the definition of neighbours.

**Geary’s C**

In this case the interaction is not the cross-product of the deviations from the mean, but the deviations in intensities of each observation location with one another. It is inversely related to Moran’s I. It does not provide identical inference because it emphasizes the differences in values between pairs of observations, rather than the covariation between the pairs. Moran’s I gives a more global indicator, whereas the Geary coefficient is more sensitive to differences in small neighborhoods.

$$C = \frac{[(N - 1)\sum_i \sum_j W_{ij} (X_i - X_j)^2]}{2(\sum_i \sum_j W_{ij} (X_i - \bar{X})^2)}$$

**Spatial Interpolation**

Spatial interpolation describes a process of using points with known values to estimate values at other points i.e it is the procedure of predicting the values of attributes at unsampled sites from measurements made at point locations within the same area or region. Interpolation is used to convert the data from point observations to the continuous fields so that the spatial patterns sampled by these measurements can be compared with the spatial patterns of other spatial entities. Spatial interpolation is thus a means of converting point data into surface data. It is a process of using points with known values to estimate values at other points forming the surface. For example while mapping precipitation if there is no weather reporting station within the grid cell, an estimate is based on nearby weather stations. The rationale behind interpolation is that, on average, values of the attribute are more likely to be similar at points close together than at those further apart.

The word "kriging" is synonymous with spatial interpolation. It is a method of interpolation which predicts unknown values from data observed at known locations. This method uses variogram to express the spatial variation, and it minimizes the error of predicted values which are estimated by spatial distribution of the predicted values. Kriging is also the method that is associated with the acronym B.L.U.E. (best linear unbiased estimator.) It is "linear" since the estimated values are
weighted linear combinations of the available data. It is "unbiased" because the mean of error is 0. It is "best" since it aims at minimizing the variance of the errors. The difference of kriging and other linear estimation method is its aim of minimizing the error variance.

**Semivariogram**

Semivariance is a measure of the degree of spatial dependence between samples. The magnitude of the semivariance between points depends on the distance between the points. A smaller distance yields a smaller semivariance and a larger distance results in a larger semivariance. The plot of the semivariances as a function of distance from a point is referred to as a semivariogram. The semivariance increases as the distance increases until at a certain distance away from a point the semivariance will equal the variance around the average value, and will therefore no longer increase, causing a flat region to occur on the semivariogram called a sill. From the point of interest to the distance where the flat region begins is termed the range or span of the regionalized variable. Within this range, locations are related to each other, and all known samples contained in this region, also referred to as the neighborhood, must be considered when estimating the unknown point of interest. Further for h zero, the value of semivariance should strictly be zero but due to several factors, such as sampling error or short scale variability, may cause sample values separated by extremely small distances to be quite dissimilar. This causes a discontinuity at the origin of the variogram. The vertical jump from the values of zero at the origin to the value of the variogram at extremely small separation distances is called the nugget effect. The figure below shows a general semivariogram.

**Ordinary Kriging**

Ordinary kriging gives both a prediction and a standard error of prediction at unsampled locations. The aim of kriging is to estimate the value of a random variable \( z \) at one or more unsampled points or over large blocks from more or less sparsed data say \( z(x_1), \ldots, z(x_N) \) at \( x_1, \ldots, x_N \). The data may be distributed in one, two or three dimensions, though applications in the agricultural sciences are usually two-dimensional. It assumes that the mean is unknown, we estimate \( Z \) at a point \( x_0 \) by \( \hat{Z}(x_0) \), with the same support as the data, by
\[ \hat{Z}(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i) \]

Where \( \lambda_i \) are weights. To ensure that the estimate is unbiased, the weights are made to sum to 1.

\[ \sum_{i=1}^{N} \lambda_i = 1 \]

and the expected error is \( \text{E} [\hat{Z}(x_0) - Z(x_0)] = 0 \).

The estimation variance is

\[ \text{var} [\hat{Z}(x_0)] = \text{E} [ (\hat{Z}(x_0) - Z(x_0))^2 ] \]

The kriging equations can be represented in matrix form as

\[ A \lambda = b \]

Where,

\[ A = \begin{bmatrix} \gamma(x_1,x_1) & \gamma(x_1,x_2) & \cdots & \gamma(x_1,x_N) & 1 \\ \gamma(x_2,x_1) & \gamma(x_2,x_2) & \cdots & \gamma(x_2,x_N) & 1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \gamma(x_N,x_1) & \gamma(x_N,x_2) & \cdots & \gamma(x_N,x_N) & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \]

\[ \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_1 \\ \vdots \\ \vdots \\ \lambda_1 \\ \psi(x_0) \end{bmatrix} \text{ and } b = \begin{bmatrix} \gamma(x_1,x_0) \\ \gamma(x_2,x_0) \\ \vdots \\ \vdots \\ \gamma(x_N,x_0) \\ 1 \end{bmatrix} \]

Where,

\( \gamma(x_i, x_j) = \text{semivariance of } Z \text{ between the data points } x_i \text{ and } x_j. \)

\( \gamma(x_i, x_0) = \text{semivariance of } Z \text{ between the data points } x_i \text{ and } x_0. \)

The weights and the Lagrange multiplier are obtained as

\( \lambda = A^{-1} b \)

The kriging variance is given by
\[ \hat{\sigma}^2(x_0) = b^T \lambda \]

Ordinary kriging is an exact interpolator in the sense that when equation given above is used, the interpolated values, or best local average, will coincide with the values at data points.

**Simple Kriging**

Sometimes we know the mean of a random variable from the previous experience or we can assume it from the nature of the problem. In these circumstances to improve our estimates, we go for simple kriging, for simple kriging the equation is

\[ \hat{Z}_{sk}(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i) + \left\{1 - \sum_{i=1}^{N} \lambda_i\right\} \mu \]

The weights are found by solving

\[ \sum_{i=1}^{N} \lambda_i \gamma(x_i, x_j) = \gamma(x_0, x_j) \quad \text{for} \quad j = 1, \ldots, N \]

And the kriging variance is given by

\[ \sigma^2_{sk}(x_0) = \sum_{i=1}^{N} \lambda_i \gamma(x_i, x_0) \]

In general the variances obtained by simple kriging are somewhat smaller than those from ordinary kriging.

**Universal Kriging**

Some spatial processes comprise both stochastic and deterministic components, and we represented them by the model

\[ Z(x) = \sum_{k=0}^{K} a_k f_k(x) + \varepsilon(x) \]

In this equation the drift is represented by a set of functions, \( f_k(x) \), \( k=0, 1, \ldots, K \), of our choosing and unknown coefficients \( a_k \). \( \varepsilon(x) \) is the stochastic component, the variogram of which we shall wish to use for kriging. We compute a variogram of the residuals from the drift from the regularly spaced data, now we give the formulae for kriging using that variogram called universal kriging.

**Spatial Sampling**

Spatial sampling is that area of survey sampling which is concerned with sampling in two dimensions like the sampling of fields, groups of contiguous quadrats or other planar surface. Spatial sampling is difficult problem to deal with, since the idea is to select an unbiased sample, but finding independent observations are impossible. One approach to spatial sampling is through
a population of MN units, usually points or quadrats, arranged in M rows and N columns. The sampling designs to choose mn units fall into three distinct types: designs in which the sample units are aligned in both the rows and column directions; designs in which the sample units are aligned in one direction only, say the rows, and unaligned in column directions; designs in which the sample units are unaligned in both the directions. For designs that have the sampling units aligned in both the directions, the number of sample elements in any row of the population will be 0 or n and the number of sampled elements in any column of the population will be 0 or m. For designs that have sampled units aligned in the rows and unaligned in column, the number of sample elements in any row of the population will be 0 or n and the number of sampled elements in any column will be at most m. Designs that have sample units unaligned in both the directions are characterized by having at most n sample elements in any row and at most m elements in any column of the population with the exception of simple random sampling without replacement of mn units from the MN in the population. Three traditional sampling designs have generally been applied for selection of the sampling units in different ways such as (a) simple random sample of row/columns, (b) a stratified sample of rows and for each selected row independent stratified sample of columns and (c) a systematic sample unaligned in both the directions.

A second approach to spatial sampling is in a more general population structure, where the spatial population is composed of a number of non-overlapping domains. Without imposing any more structure on the population, three sampling schemes can be considered: random sampling, stratified sampling and systematic sampling.

Dependent Areal Unit Sequential Technique (DUST) is a GIS based sequential technique characterized by variable inclusion probabilities at each step. The principle for sample selection for DUST is that the probability of selection of any unit increases as the distance from the areas already sampled increases. The steps for DUST includes estimation of spatial correlation coefficient (β) for the auxiliary variable x at various spatial lags and stationarity testing at various order spatial correlations followed by sample selection. The first unit is selected randomly out of N units. The subsequent units are selected by applying weight \( W_n = \prod_{i=1}^{n-1} \left(1 - \beta d_{in}\right) \) for the units selected at the nth draw. β is the spatial correlation for the auxiliary character, n is the sample size and \( d_{in} \) is the distance between ith and nth units. Suitable estimators are used for estimation of population parameters.

**Spatial Regression**
Regression is often used in analysis of spatial data to obtain predictive relationships between variables. The assumption that the errors from the regression model are statistically independent will often not be plausible, due to spatial dependence in the sources of error. This is a problem for the regression analysis resulting in estimation of the standard deviation of the errors from the model is biased (downwards) which invalidates confidence limits on predictions made with the model, and which could lead to a false conclusion that the regression is statistically significant. While the estimates of the regression coefficient(s) are not necessarily biased they are not minimum-variance estimates when the errors are correlated.

Regression is used to estimate an equation for predicting a dependent variable from values of one or more independent variables. The most useful applications of regression analysis are where the independent variable(s) can be rapidly collected at low unit cost by comparison to the dependent variable. A limited number of costly observations of the dependent variable may then be used to compute the regression equation, which is then applied to predict the dependent variable for all locations where the independent variables are measured. There are many examples of this
application of regression analysis. Variables computed from digital elevation models have served as independent variables to predict soil properties, crop yields and air temperatures. Remote sensor data have been used as the independent variables to predict vegetation variables, water quality and forest resources. Regression has been used to predict soil salinity (measured directly by auger sampling and laboratory analysis) from measurements of electromagnetic induction.

References

What is APSIM?

APSIM (the Agricultural Production Systems Simulator) is a farming systems computer model that simulates the effects of environmental variables and management decisions on production (crops, pasture, trees, and livestock), profits and the environmental variables (e.g. soil erosion). It can be used to analyse risk and explore alternative management options such as crop choice, planting date and fertilizer rate, using local climate data and paddock-specific soil data. When used interactively with farmers, it can also take into account the social and/or economic values or goals that influence an individual farmer’s management decisions. An important feature of APSIM is its ability to integrate sub-models from different research domains or even different disciplines. This allows research from one domain or discipline to benefit another domain or discipline. It also allows researchers to compare sub-models on a common platform. For a given production scenario, APSIM can estimate profitability, economic risk, yield, animal production and effects on the environment. For given characteristics of the plant species and varieties, livestock species, breeds and age classes, soil water and fertility and management, APSIM can simulate, day by day:

- Plant growth (crops, pasture, trees, weeds)
- Animal live weight gain, reproduction, wool production
- Soil processes (water balance, solutes, nitrogen, phosphorus, carbon, pH)
- Surface residue dynamics (e.g. rate of stubble decomposition) and erosion
- Dry land or irrigated systems
- A range of management options (e.g. different sowing dates)
- Crop rotations, fallowing and combinations of these
- Pests and diseases
- Short- or long-term effects.

History of APSIM

In 1990 the Agricultural Production Systems Research Unit (APSRU), was formed jointly by CSIRO and the Queensland Government (the then Department of Primary Industries). Its mission was to benefit rural industries and the environment through innovative systems approaches to research and development. Located in Toowoomba, Queensland, Australia, the research unit aimed to use its expertise in the computer simulation of farming systems to support research that would improve how cropping production systems are managed. Through discussions with farmers, APSRU identified a need for tools that accurately predicted crop production in relation to climate, genotype, soil, and management while addressing the long-term resource-management issues. APSRU developed APSIM in response to this need. In 2009, responsibility for developing, maintaining and commercializing APSIM moved from the research-oriented APSRU to the APSIM Initiative—an agreement between CSIRO, the Queensland Government Department of Employment, Economic Development and Innovation and The University of Queensland to promote the development and use of APSIM. The initiative is managed by a steering committee which receives advice from a reference panel on APSIM development matters. The reference panel encourages collaboration and innovation on APSIM’s science functionality and software development process, and oversees and manages all APSIM software development. In the spirit of collaborative community-source software development, licensed users (individuals and organizations) have access to the source code and may submit software changes and new modules.
for the reference panel to evaluate. Access to APSIM source code is through the APSIM Community Source Framework.

**APSIM's modules**

The APSIM modeling framework (Fig. 1) is made up of the following components:

- A set of biophysical modules that simulate biological and physical processes in farming systems.
- A set of management modules that allow the user to specify the intended management rules that characterize the scenario being simulated and that control the simulation.
- Various modules to facilitate data input and output to and from the simulation.
- A simulation engine that drives the simulation process and facilitates communication between the independent modules.

In addition to the science and infrastructure elements of the APSIM simulator, the framework also includes:

- Various user interfaces for model construction, testing and application
- Various interfaces and association database tools for visualization and further analysis of output.
- Various model development, testing and documentation tools.
- A web based user and developer support facility that provides documentation, distribution and defect/change request tracking.

![Diagram of APSIM simulation framework](image)

**Figure 1:** Diagrammatic representation of the APSIM simulation framework with individual crop and soil modules, module interfaces and the simulation engine.

APSIM's plant, stock, environment and management modules support a diverse range of crops, pastures and trees, soil processes, nitrogen and phosphorus transformations, soil pH, erosion and a full range of management controls. The plant/animal and environment modules simulate biological and physical processes in farming systems. APSIM supports more than 30 crops (such as wheat, sorghum, sugarcane, barley, grapevine, oats, cotton and rice), pastures (such as Rhodes...
grass), stock (cattle and sheep), tree species (such as Eucalyptus and Pinus radiata), weeds, parasites and rodents. Environment modules handle variables such as climate and weather, soil characteristics (e.g. water balance, nutrients, pH, and temperature), crop residue, and erosion. Management modules allow management rules for a given scenario to be specified, including variables related to sowing, harvesting, fallowing, tillage, irrigation, fertiliser use, grazing management, stocking rate, and crop mix.

**How is APSIM used?**
APSIM can be applied in multiple domains such as:

- Climate variability and change – to evaluate management options
- Agronomic practice – to support decision making for improved production and environmental benefits
- Assessing land-use options – to quantify the trade-offs of alternative systems (e.g. carbon farming)
- Gene-to-phenotype modeling and breeding – to support crop breeding efforts.

It has been used around the world in a broad range of applications, including:

- Supporting on-farm decision making
- Designing farming systems for production or resource-management objectives
- Assessing the value of seasonal climate forecasting
- Analyzing supply-chain issues in agribusiness
- Developing waste-management guidelines
- Assessing risk for government policymaking
- Guiding research and education
- Guiding crop breeding strategies.

**Creating an APSIM met file using Excel.**
APSIM met files consist of a section name, which is always “weather.met.weather”, several constants consisting of name = value, followed by a headings line, a units line and then the data. Spacing in the file is not relevant. Comments can be inserted using the “!” character. At a minimum three constants must be included in the file: latitude, tav and amp. The last two of these refer to the annual average ambient temperature and annual amplitude in mean monthly temperature. The met file must also have a year and day column (or date formatted as yyyy/mm/dd), solar radiation (MJ/m2), maximum temperature (°C), minimum temperature (°C) and rainfall. The column headings to use for these are year and day (or date), radn, maxt, mint, rain.

(1) To create met file through Microsoft EXCEL, open EXCEL and enter data into columns like this:
The next step is to save this file as formatted text (space delimited) with “.met” extension.

The next step is to download two small software namely “Tav_Amp” and “tamet” from http://www.apsim.info.

**Tav_Amp:**
Calculate values of annual average ambient temperature (TAV) and annual amplitude in mean monthly temperature (AMP) for an APSIM climate (met) file and insert these values with keywords into the file.

Apsim-SoilN2 (SoilN2) model uses the TAV and AMP to calculate the daily soil temperature for a site. These two variables are read by SoilN2 from its site parameter file and are used as default values for the site. If SoilN2 is unable to obtain these values from another APSIM module, such as the Met or Manager modules, it will use these default values. Tav_Amp has been constructed to calculate and insert the TAV and AMP values into the keyword portion of an APSIM climate file so that the Met module can provide these values on request by SoilN2. Tav_Amp is a Lahey Fortran90 program compiled and linked to for 32 bit operation.

Amp is obtained by averaging the mean daily temperature of each month over the entire data period resulting in twelve mean temperatures, and then subtracting the minimum of these values from the maximum. Tav is obtained by averaging the twelve mean monthly temperatures. Tav_Amp reads a nominated met file, calculates the values for TAV and AMP and writes a new met file with the calculated values inserted after the TAV and AMP keywords, which are placed immediately before the column headers. A comment is inserted before these new lines which specifies the date and time of insertion and the start and end of the period over which the data is calculated. Any existing TAV and AMP keyword and comment lines are removed. Ambient temperature is calculated by averaging the maximum and minimum temperatures of the day. Before reading the temperature data columns, the
column headers are identified by the text strings, year, maxt and mint which are not within a comment.

**Important:** Tav_Amp is run from a DOS prompt or the Windows Run command and requires the input and output file names to be specified after ‘Tav_Amp’.

**Syntax used in MS-DOS command for creating met file**

```
Tav_Amp [drive:][path]input_filename [drive:][path]output_filename
```

**Where:**

- **[Drive:]**[Path]input_filename - The name of the input file and optionally its path, up to 255 characters including the path.
- **[Drive:]**[Path]output_filename - The name of the output file and optionally its path, up to 255 characters including the path.

(4) Open the MS-Dos window through typing “cmd” in “Run” command. MS-Dos window looks like as follows:

![MS-Dos window](image)

(5) The next step is to write the path of **tav_amp**, input and output file in the MS-DOS window and press the enter button.
While Tav_Amp is running, it reports its progress as it analyses the input file by displaying information about its actions in a window.

(6) An Example of *met* file:

Limits in creating the *met* file:

- Maximum length of file names with paths is 255 characters.
- Maximum source file line length is 200 characters.
- Maximum number of data columns is not more than 20.
- Year range must be in between 1850 to 2020 inclusive.

Using Tamet:

This program was originally developed by B. H. Wall of the CSIRO Div. of Tropical Crops and Pastures in 1977. While the original fortran implementation would produce a (long winded) report, modern version comes as a simple GUI that displays potential errors in place, allowing you to directly edit the data and save your changes.
Using the program is simple – After met files are opened (through the file menu), the data is scanned by pressing the lower right button. Once the file is scanned, the “prev” and “next” buttons allow you to move quickly between any warnings tamet has found. You can make changes to the data and save it. Parameters for each of the tests can be changed in the ‘Parameters’ panel. The file needs to be ‘scanned’ again before the results of these changes are seen. The complete list of tests is listed in the ‘Notes’ panel.

Soil: Picking a soil file involves finding a suitable soil from the Soils toolbox. To open the toolbox just click on the Soils button on the toolbar at the bottom of the window. The Soils toolbox has many soils to choose from. Drag your chosen soil from the toolbox and drop into the paddock on the simulation tree. You can then delete the existing soil in the paddock as it is no longer needed. Once the soil has been dropped it can be modified by clicking on it and then modifying the parameters to the right.
The starting water that a simulation initialises with can be found by expanding the soil component in the simulation tree and then clicking InitWater. The initial water can be specified in multiple ways by selecting one of the radio buttons and then entering a percent water or mm water. All changes made are automatically reflected in the graph on the right. By selecting Specify waters layered values, you are able to directly enter the values in the soil water grid.
The starting nitrogen that a simulation initialises with can be found under the InitNitrogen node under the soil in the Simulation tree.

**Surface Residues / Organic Matter:** The parameters for the initial surface residues can be found under the surface organic matter component in the simulation tree.

The "Organic Matter pool name" is simply an alphabetic description of the residue pool. The more important parameters are the "Organic matter type" and "Initial surface residue," "C: N ratio of initial residue" and the "Fraction of residue standing."

**Fertilizer:** This component does not have any editable parameters. This component only needs to be present if you are going to be doing fertilizer applications in your simulation.

**Crops:** Crops can be dragged from the Standard Toolbox and dropped onto a paddock. A crop can be deleted by selecting it and pressing Delete. Crops typically don't have any editable parameters.

**Simulation management**

The Manager component contains all the management options for the simulation.
- Sowing
- Fertilizing
- Irrigation
- Tillage
- Resetting of water and nitrogen
- Rotations

These options can be dragged from the Standard toolbox (under Manager) and dropped under a Manager component within a paddock.

APSIM is capable of producing an ASCII space separated output file containing whatever APSIM variables you want. In fact, you need to exactly specify which variables you want output to the file. This is all configured from the Output file component. Expand the output file component and click Variables and drag the desired variable.
An Overview of APSIM

APSIM (Agricultural Production Systems Simulator) was developed by the Agricultural Production Systems Research Unit (APSRU), a collaborative group made up from CSIRO and Queensland State (Australia) Government agencies. The APSIM modelling framework is made up of:

a) A set of biophysical modules that simulate biological and physical processes in farming systems.

b) A set of management modules that allow the user to specify the intended management rules that characterize the scenario being simulated and that control the conduct of the simulation.

c) Various modules to facilitate data input and output to and from the simulation.

d) A simulation engine that drives the simulation process and controls all messages passing between the independent modules.

APSIM comes with a user interface that lets users configure simulations using a drag and drop paradigm. This interface provides complete access to all APSIM parameters and supports multiple point simulations. When you install APSIM on your PC, a APSIM user interface (APSIMUI) icon will be created on the desktop. When first started (by double clicking the ApsimUI icon from the Apsim icon on your desktop), the interface shows a toolbar at the top and a toolbar at the bottom and two empty panes in between.

To create a simulation, click New and select a simulation that is closest to the type of simulation you want to build. Here, we select “continuous wheat simulation” option.

After selecting “continuous wheat simulation,” one new window will appear with tree control on the left side, which shows the components that make up the simulation. Clicking on a component will show the properties for that component on the right. The picture below shows the different component selected with its properties on the right.
**Met component:** The weather properties are located under the Met component in the simulation tree. There you will have the ability to browse to a weather file. Weather files need to be in APSIM format and should have a .met extension. A few sample weather files can be found in the \Examples\MetFiles directory under your apsim installation. After this, model need the start and end date of simulation. These two properties can be found under the Clock component. They need to be within the range of the weather file.

In APSIM, there is option to add components to a simulation tree, click the Standard button on the toolbar at the bottom of the window. This will show the standard toolbox containing many components and simulation entities that can be dragged onto the simulation tree.
Picking a soil file involves finding a suitable soil from the Soils toolbox. To open the toolbox just click on the Soils button on the toolbar at the bottom of the window. The Soils toolbox has many soils to choose from. Drag your chosen soil from the toolbox and drop it into the paddock on the simulation tree. You can then delete the existing soil in the paddock as it is no longer needed. Once the soil has been dropped it can be modified by clicking on it and then modifying the parameters to the right.

The starting water that a simulation initialises with can be found by expanding the soil component in the simulation tree and then clicking InitWater. The initial water can be specified in multiple ways by selecting one of the radio buttons and then entering a percent water or mm water. All changes made are automatically reflected in the graph on the right. By selecting Specify waters layered values, you are able to directly enter the values in the soil water grid.
The starting nitrogen that a simulation initializes with can be found under the InitNitrogen node under the soil in the Simulation tree.

Surface Residues / Organic Matter: The parameters for the initial surface residues can be found under the surface organic matter component in the simulation tree. The "Organic Matter pool name" is simply an alphabetic description of the residue pool. The more important parameters are the "Organic matter type" and "Initial surface residue," "C: N ratio of initial residue" and the "Fraction of residue standing."
**Fertilizer:** This component does not have any editable parameters. This component only needs to be present if you are going to be doing fertilizer applications in your simulation.

**Crops:** Crops can be dragged from the Standard Toolbox and dropped onto a paddock. A crop can be deleted by selecting it and pressing Delete. Crops typically don't have any editable parameters.

**The APSIM Soil Water Module**

In APSIM there is a module for the soil water balance, known as SOILWAT. It is a cascading layer model that owes much to its precursors in CERES Jones and Kiniry, 1986) and PERFECT (Littleboy et al., 1992). It operates on a daily time step. The water characteristics of the soil are specified in terms of the lower limit (LL15) drained upper limit (DUL) and saturated (SAT) volumetric water contents of a sequence of soil layers. The thickness of each layer is specified by the user; typically, layer thickness of 100 or 150 mm is used for the uppermost layer and 300-500 mm at the base of the profile; the whole profile might be represented by up to 10 or more layers. As with all layered models, the empirical soil parameters are influenced by the number and thickness of specified layers.

The following diagram is showing the communication between SOILWAT and other APSIM modules.
Communication between Soil Water and other APSIM modules

Climate change and crop simulation modelling

Climate change
Climate change is defined as “Any long term substantial deviation from present climate because of variations in weather and climatic elements.”

The causes of climate change
1. The natural causes like changes in earth revolution, changes in the area of continents, variations in the solar system, etc.
2. Due to human activities, the concentrations of carbon dioxide and certain other harmful atmospheric gases have been increasing. The present level of carbon dioxide is 325 ppm, and it is expected to reach 700 ppm by the end of this century, because of the present trend of burning forests, grasslands and fossil fuels. Few models predicted an increase in average temperature of 2.3 to 4.6oC and precipitation per day from 10 to 32 per cent in India.
**Green house effect**

The effect because of which the earth is warmed more than expected due to the presence of atmospheric gases like carbon dioxide, methane and other tropospheric gases. The shortwave radiation can pass through the atmosphere easily, but the resultant outgoing terrestrial radiation cannot escape because the atmosphere is opaque to this radiation and these acts to conserve heat, which raises the temperature.

**Effects of climate Change**

- a. The increased concentration of carbon dioxide and other green house gases are expected to increase the temperature of earth.
- b. Crop production is highly dependent on variation in weather and therefore, any change in global climate will have major effects on crop yields and productivity (Fig. ).
- c. Elevated temperature and carbon dioxide affect the biological processes like respiration, photosynthesis, plant growth, reproduction, water use, etc. In case of rice increased carbon dioxide levels results in a larger number of tillers, greater biomass and grain yield. Similarly, in groundnut increased carbon dioxide levels results in greater biomass and pod yields.
- d. However, in tropics and sub-tropics the possible increase in temperatures may offset the beneficial effects of carbon dioxide and results in significant yield losses and water requirements. Proper understanding of the effects of climate change helps scientists to guide farmers to make crop management decisions such as selection of crops, cultivars, sowing dates and irrigation scheduling to minimize the risks.

The increasing CO₂ concentration in the atmosphere and the anticipated temperature rise due to global warming are also likely to affect agricultural production in the world through changes in plant growth and transpiration. Soybean [*Glycine max* (L.) *Merrill*] is one of the most important oilseeds cultivated in India and it is the part of the soybean-wheat cropping systems, a dominant cropping system in central India. Area under soybean cultivation has steadily increased over the years in the states like, MP, Chhattisgarh, and Maharastra. Future climatic change is likely to have substantial impact on soybean production depending upon the magnitude of variation in temperature. Increased temperature significantly reduces the grain yield due to faster growth and decreased time to accumulate grain weight (Baker et al., 1989). There have been a few studies in India and elsewhere aimed at understanding the nature and magnitude of gains/losses in yields of soybean crop at different sites under elevated atmospheric temperature conditions. Wheat (*Triticum aestivum*, L.) crop is also subjected to the adverse effect of climate change in future. So, the lecture note discuss the effect of climate change on a few major crops in India as examples and how different adaptation strategies will taken to avoid this impact of climate change on productivity of these crops.

**The climate change scenario**

The Intergovernmental Panel on Climate Change (IPCC, 2001) reported that the average global surface temperature will increase by between 1.4 and 3 °C above 1990 levels by 2100 for low emission scenarios and between 2.5 and 5.8 °C for higher emission scenarios of greenhouse gases and aerosols in the atmosphere. Over the land regions of the Indian subcontinent, the projected (area-averaged) annual mean surface temperature rise by the end of 21ᵗʰ century has been estimated to range between 3.5 and 5.5 °C depending upon the future trajectory of anthropogenic radiative forcing (Lal et al., 2001). The projected temperature increase has a large seasonal and spatial dependency over India. During the monsoon season, the temperature rise over south India is projected to be less than 1.5 °C by 2050s while the increase in surface temperature is more
pronounced over north, central and east India (>2 °C). Probable changes in precipitation, cloudiness and solar radiation under the climate changes scenarios were not taken into consideration in this analysis in view of the significant uncertainties associated with non-linear, abrupt and threshold rainfall events projected by GCMs over the Indian subcontinent.

**Role of APSIM in climate change research**

In recent years there has been a growing concern that changes in climate will lead to significant damage to both market and non-market sectors. The climate change will have a negative effect in many countries. However, farmers adaptation to climate change-through changes in farming practices, cropping patterns, and use of new technologies will help to ease the impact. The variability of our climate and especially the associated weather extremes is currently one of the concerns of the scientific as well as general community. The application of crop models to study the potential impact of climate change and climate variability provides a direct link between models, agrometeorology and the concerns of the society.

**Impact of increase in surface air temperature on soybean and wheat yield**

The increased in surface air temperature has tremendous effect on soybean as observed in long-term simulation by the APSIM model. The results revealed that there was significant decrease in yield of soybean from the normal (base line followed) (Fig. 1). The base line yield for this study was the long-term simulated yield of 16 years under recommended management practices followed for soybean. The probability distribution of soybean yield, presented in Fig. 1, described the probability of obtaining a specific amount of grain yield under the increased temperature scenario. The Fig. 1 presented that there is 50% probability of obtaining <1 t ha$^{-1}$ of soybean grain yield under climate change scenario as predicted by the model, whereas the probability of getting same amount of grain yield under normal condition is observed to be <10%. So, the increased surface temperature by 3 degree during soybean growing season decreased the yield significantly which suggested that in future due to climate change the yield of soybean is going to decrease to the tune of about 30%. To reduce the impact of climate change it is necessary adopt new management practices so that the soybean crop can adapt to new environment. This is possible either by changing the dates of sowing or by changing the plant density. Increase in surface temperature also decreased the wheat yield. This decrease followed similar trend as observed in case of soybean in all the years of simulation studies.
Table 2. **Mean predicted change in soybean yield under the fixed temperature and CO\textsubscript{2} scenarios (Bhopal)**

<table>
<thead>
<tr>
<th>CO\textsubscript{2} concentration (ppm)</th>
<th>Temperature (°C)</th>
<th>Base</th>
<th>+2</th>
<th>+4</th>
<th>+5</th>
</tr>
</thead>
<tbody>
<tr>
<td>390</td>
<td></td>
<td>0%</td>
<td>-19%</td>
<td>-26%</td>
<td>-27%</td>
</tr>
<tr>
<td>450</td>
<td></td>
<td>+10%</td>
<td>-19%</td>
<td>-23%</td>
<td>-23%</td>
</tr>
<tr>
<td>550</td>
<td></td>
<td>+23%</td>
<td>-18%</td>
<td>-19%</td>
<td>-20%</td>
</tr>
<tr>
<td>650</td>
<td></td>
<td>+32%</td>
<td>-15%</td>
<td>-17%</td>
<td>-18%</td>
</tr>
</tbody>
</table>

Increase in CO\textsubscript{2} concentration increased the soybean yield whereas increase in temperature decreased soybean yield. The decrease was less when temperature in CO\textsubscript{2} in combination was used for simulation (Table 2).

Increasing temperature reduced mustard grain yield, while increase in CO\textsubscript{2} concentration increased crop yield. Increase in CO\textsubscript{2} from 369 to 550 ppm with no change in temperature has resulted in 15.8–31% increase in yield of irrigated mustard across different regions. Positive yield response of mustard to elevated carbon dioxide was due to, increased photosynthetic activity resulting in increased specific leaf area, leaf weight, biomass production and grain number. But the positive effect of increase in CO\textsubscript{2} concentration was nullified by temperature rise. Under irrigated condition, the grain yield dropped steeply with rise in temperature in eastern India. In this region, yield reduction was maximum (86.6%) with 5 °C rise in temperature. Rise in temperature coupled with rise in CO\textsubscript{2} to 450 and 550 ppm decreased yield reduction to 82.4 and 79.4% respectively. Yield reduction of mustard was moderate in northern part of the country (Fig. 3). In north India, temperature rise by 5 °C, with no rise in CO\textsubscript{2} reduced mustard yield by 34.7%. Rise in CO\textsubscript{2} along with temperature caused less yield reduction of mustard in this region. Mustard crop grown in central part of the country was also vulnerable to temperature rise, where substantial yield loss was observed. Temperature rise would be most harmful for the crop in eastern region, followed by central India, where winter season temperature is comparatively higher than northern region. Further rise in temperature in these locations would cause substantial yield reduction in this crop.

**Adaptation strategies for soybean crop to increased temperature scenario using APSIM model**

To reduce the impact of climate change on soybean crop, it is necessary that the new management practices to be followed in future. It is possible to reduce the further reduction in grain yield of the same cultivar by adopting new management practices or by total replacement of the cultivar either by another cultivar which can sustain growth under increased temperature condition or breeding to develop new cultivars. Here in this study we developed adaptation strategies to increased temperature of soybean crop by changing the dates of sowing and plant population.

The increased temperature to the tune of 3° C resulted in reduction in grain yield by 33% when the sowing date of soybean was 20\textsuperscript{th} June. But by advancing the sowing date beyond 20\textsuperscript{th} June, it was observed that the reduction in yield was in the range of -23 to -13% from the normal (Fig. 4). By adopting the sowing date to 10\textsuperscript{th} July it was possible to reduce the impact of temperature change on soybean yield. A least reduction of about -13% was observed in 10-July sowing date. Sowing before 20\textsuperscript{th} July did not have any mitigating effect due to changed temperature on soybean yield. The change in plant density has significant effect on grain yield of any crop. So, attempt has been made by the authors to change the plant density of soybean crop to simulate the impact of increased temperature on yield. Here the chosen plant density of 60 plants m\textsuperscript{-2} was considered after a series of simulations and used for adaptation study.
It was observed that by increasing the plant population from 50 to 60 plants m$^{-2}$ increased the grain yield of soybean under the adverse impact of climate change (Fig. 5). There was further increase in grain yield of soybean by coupling advanced sowing dates and increased plant population. The decrease in grain yield due to increased temperature was reduced to -15, -11 and -16% in sowing dates of 30-June, 10-July and 20-July respectively. So, from the study it was revealed that agronomic management practices such as changing sowing dates and plant population could reduce the impact of climate change on crop yield to considerable extent.

**Future research and development**

Crop models are in an infant stage of development. Most models only simulate the major factors that affect crop performance, e.g., weather, water, and soil nitrogen availability. Missing are components to predict the effects of tillage, pests, weeds, salinity, excess water, and other factors on crop performance. To use crop models and the systems approach for more effective resource
management, simulation models for all the major crops incorporated into cropping rotations for that region are needed.

Many crop models use genetic coefficients to simulate crop growth and development. Employing cultivar-specific characteristics generally improves model performance and enables the model to analyze cultivar adaptation to diverse environments. In the past, these coefficients were usually not adequately determined. To prevent the unavailability of these coefficients from becoming the bottleneck in model applications, support for determining crop-specific coefficients is needed. The desired outcome would be having the proper genetic coefficients available when new cultivars are released so that the suitability of a new cultivar for a region can be quickly evaluated. Improvements in the technology and accuracy of crop modelling have convinced many scientists that the routine use of crop models for agricultural decision-making is a desirable goal. Thus, knowledge-based systems-approach research will gradually increase in importance relative to experience-based conventional agronomic research. Crop models will become an important mechanism for synthesizing the existing knowledge about plants and resources and for updating this knowledge as we learn more about complex agricultural systems. Eventually, the system model will become the primary agent for technology transfer, replacing the traditional extension short courses and handbooks.

Reference


Robertson, M.J., Sakala, W., Benson, T., Shamudzarira, Z., 2005. Simulating response of maize to previous velvet bean (Mucuna pruriens) crop and nitrogen fertilizer in Malawi. Field Crops Res. 91, 91-105.

Robertson, M.J., Sakala, W., Benson, T., Shamudzarira, Z., 2005. Simulating response of maize to previous velvet bean (Mucuna pruriens) crop and nitrogen fertilizer in Malawi. Field Crops Res. 91, 91-105.


11. Effect of organics on soil aggregate stability
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The formation and stability of the aggregates and the pores between them affects the movement and storage of water, aeration, erosion, biological activity and the growth of crops. Soil aggregation is the process by which aggregates of different sizes are joined and held together by different organic and inorganic materials. Thus, it includes the processes of formation and stabilization. In the field these processes occur more or less continuously, and concurrently. Some authors report that the formation of soil aggregates occurs mainly; as a result of physical forces, while the stabilization of soil aggregates is produced by a number of factors, in particular the quantity and quality of inorganic and organic stabilizing agents (Dalal and Bridge, 1996). However, clay flocculation is a pre-requisite for soil aggregation (Dexter, 1988).

Two main groups of factors affect soil aggregate stability viz., (i) soil primary characteristics or internal factors and (ii) external factors to the soil. Among the soil primary characteristics, influence of the electrolyte (concentration, thus electrical conductivity, EC; type of cations, sodium adsorption ratio, SAR; pH etc.), clay mineralogy, CaCO$_3$ and gypsum, organic matter, and Fe and Al oxides are important. Among the external factors, climate, time, biological factors and the agricultural management influence soil aggregation.

**The physical forces:** alternate wetting and drying (semi-arid and sub-humid regions), freezing and thawing (temperate regions), the compressive as well as drying action of roots, and the mechanical alimentary action of soil fauna, mainly earthworms, termites and ants.

**The inorganic stabilizing agents:** mainly clays, polyvalent metal cations such as Ca$^{2+}$, Fe$^{3+}$, and Al$^{3+}$, oxides and hydroxides of Fe and Al, calcium and magnesium carbonates and gypsum.

**The organic stabilizing agents** can be considered in three main groups based on the age and degradation of the organic matter: transient, temporary and persistent binding agents (Tisdall and Oades, 1982).

**The transient binding agents:** are decomposed rapidly by microorganisms and include microbial- and plant-derived polysaccharides.

**Temporary binding agents:** are roots, hyphae, particularly vesicular-arbuscular mycorrizal hyphae, and some fungi.

**Persistent binding agents:** consist of resistant aromatic humic material associated with polyvalent metal cations, and strongly sorbed polymers (Tisdall and Oades, 1982). These humic materials appear to be physically protected within clay- and silt-sized aggregates (Skjemstad et al., 1993). They are derived from the resistant fragments of roots, hyphae, bacteria cells and colonies.

**Role of Organic Matter in soil aggregation**

The role of organic matter (OM) with regard to aggregate stability is still controversial. Addition of organic anions (fulvates, citrates, oxalates, tartrates, salicylates, aspartates, lactates, and acetates) to soil suspensions increases clay dispersion (Shanmuganathan and Oades, 1983; Heil and Sposito, 1995). Van den Broek (1989) observed that addition of small amounts of fulvic and citric acids to clay suspensions notably increased clay dispersion, whereas aromatic acids (salicylic and hydroxybenzoic) have a flocculating effect. Visser and Caillier (1988) also showed the dispersive effect of humic substances. On the other hand, there have been numerous positive correlations between organic matter and water stable aggregates, WSA (Benito Rueda and Dfaz Fierros Viqueira, 1989; Mbagwu and Piccolo, 1989; and Fortun et al., 1989).

This apparent contradiction on the effects of OM comes from the comparison of OM with stability parameters such as WSA, and Dispersed Clay, DC. Considering that increasing WSA increases aggregate stability, it can be concluded that OM increases aggregate stability.
Considering that increasing clay dispersion decreases aggregate stability, it can be concluded that OM decreases aggregate stability. The paradox can be understood in part if we separate aggregate stability in macro-aggregate stability and micro-aggregate stability. WSA reflects macro-aggregate stability whereas DC reflects micro-aggregate stability.

There are more likely three main hypotheses to explain the apparent contradiction. First, both stability parameters emphasize different aspects of stability, macro-aggregate stability and micro-aggregate stability. Second, the effect depends on the type of union between the humic substances and the clay, and in particular, on the size of the organic anions. Only if the organic anion is longer than the clay edge, it will attach to the edges of several clay particles and bind them together (Durgin and Chaney, 1984 and Shanmuganathan and Oades, 1983). Third, OM acts differently at the two levels, macro-aggregates and micro-aggregates.

Thus, organic bonds stabilize aggregates against slaking and disaggregation, but once these bonds are broken and disaggregation has occurred, the organic matter acts as a deflocculant (Itami and Kyuma, 1995). In this sense Nadler et al. (1996b) suggested that the effect of organic matter on soil structure is a function of the size scale of the soil particles analyzed. Thus, in clay-sized aggregates, organic matter acts over the particle charge (Goldberg et al., 1990), whereas in coarse sand-sized aggregates, organic matter acts as a binding agent, through roots and hyphae (Tisdall and Oades, 1982). Thus, OM would have different effects on macro-aggregation than on micro-aggregation. Heil and Sposito (1993b) found that the effect of organic matter in clay-sized aggregates (colloidal stability) was not caused by electrostatic mechanisms (changing the particle charge), but by steric mechanisms. Steric mechanisms consist of steric repulsion resulting from the overlap of adsorbed organic polymers. The polymer coating acts as a hard surface, and limits the closest approach of two coated particles to twice the thickness of an adsorbed layer, reducing the effectiveness of attractive short-range van der Waals forces between mineral particles (Heil and Sposito, 1993b).

Other works have found no correlation between OM and WSA (Carter et al., 1994), suggesting that some components of the organic carbon pool are more actively involved in stabilizing aggregates than others (Perfect and Kay, 1990). Roberson et al. (1991) showed that densimetrically separated heavy fraction (HF) soil carbohydrate was well correlated with soil structure, while total organic C and total carbohydrate were not significantly correlated with structure. Hot-water extractable carbohydrates, which have microbial origin were postulated to be involved in soil aggregate stabilization. The stability of soil structure is more closely related to the young and active SOM fraction than to total SOM content.

In summary, the contradictory results found in the correlations among macro-aggregation and organic matter are due to one or more of the following reasons: (1) only part of the organic matter is responsible for water-stable aggregation, (2) there is a content of organic carbon above which there is no further increase in water-stable aggregation, (3) organic materials are not the major binding agents, and (4) it is the disposition rather than the type or amount of organic matter which is important (Tisdall and Oades, 1982).

The stabilizing effect of organic matter results from the combination of the transient aggregating effect of polysaccharides on micro-aggregates, the temporarily stabilizing effect of roots and hyphae on macro-aggregates, and the persistent effect of polymers and aromatic compounds on micro-aggregates. In addition, some authors have reported that another positive effect of organic matter is to form a hydrophobic coating around the aggregates, reducing soil wettability, slowing down the wetting rate, and consequently reducing the sensitivity to slaking (Blackman, 1992; Caron et al., 1996).
The dispersive effect of organic matter is the result of the following mechanisms:

1. The blocking of positively charged edges of clay minerals by negatively charged organic anions,
2. The complexation of polyvalent cations by organic matter, and
3. The steric repulsion resulting from the overlap of adsorbed organic polymer layers (Heil and Sposito, 1993a, b).

**Models of soil aggregation**

There are several models of aggregation (Edwards and Bremner, 1967; Tisdall and Oades, 1982; Elliott, 1986; Oades and Waters, 1991), and the difference among them is mainly the number of stages of aggregation (Table 1). These models confirm the hierarchical order of soil aggregation. The lowest hierarchical order is micro-aggregates less than 2 μm diameter, consisting of clay particles attached to organic molecules, (OM) by polyvalent cations (P) (Clay-P-OM). The next hierarchical order is the combination of these microaggregates (2 μm) into macro-aggregates (>250 μm). The next hierarchical order is the bonding of macro-aggregates (250 μm) into macro-aggregates (>250 μm). Finally, macro-aggregates will bind into clods (several mm or even cm). Tisdall and Oades (1982) proposed that micro-aggregates themselves are built up in stages with different types of bonds at each stage. In their model, the stages of aggregation or aggregate hierarchy were: <0.2 μm →0.2-2 μm →2-20 μm →20-250 μm →2000 μm diameter. Oades and Waters (1991) modified the model, suggesting that the stages of aggregation were: <20 μm →20-90 μm →90-250 μm →250 μm. These models can be applied generally to soils where organic matter is the main binding agent. In general, these models confirm the utility of the concept of micro and macro-aggregates to separate aggregates less and higher than 250 μm, respectively. Good soil structure is described as, "one where all the hierarchical orders are well-developed and are stable against the actions of water and external mechanical stresses" (Dexter, 1988). The hierarchical nature of soil structure indicates that different mechanisms of aggregation operate for different size classes of aggregates. Thus, macro-aggregates greater than 250 μm, and specially those greater than 2 mm in diameter, appear to be held together largely by fine roots and fungal hyphae. Aggregates 20-250 μm consist largely of particles 2-20 μm diameter bonded together by various cements including persistent organic materials and crystalline oxides and highly disordered aluminosilicates (Tisdall and Oades, 1982). Recent studies (Oades and Waters, 1991; Golchin et al., 1994) showed that encrustation of plant debris by mineral particles is another mechanism in the formation and stabilization of these micro-aggregates. For example, micro-aggregates with diameters of 2-20 μm consist of particles <2 μm diameter bonded together by persistent organic bonds (plant and fungal debris encrusted with inorganic compounds). Units smaller than 2 μm in diameter consist of clay particles held together by inorganic and organic cements and electrostatic bonds. Consequently, aggregates of different size classes will have different stability. Dexter (1988) concluded that compound particles of lower hierarchical order are denser and have a higher internal strength than particles of higher hierarchical order. He also suggested that if the lowest hierarchical order of soil structure is destroyed, the other hierarchical orders are simultaneously destroyed. Consequently, characterization of soil aggregate stability requires the analysis of the behavior of particles of different hierarchical orders, such as macro-aggregates, and clay and silt size micro-aggregates.

**Nature of organic binding agents**

The organic binding agents involved in stabilizing aggregates can be considered in three main groups based on the age and degradation of the organic matter and not on the proportions of chemically defined components. The various binding agents determine the age, size and stability
of aggregates. The three groups of organic binding agents considered are transient, temporary and persistent.

(a) Transient binding agents

Transient binding agents are organic materials, which are decomposed rapidly by microorganisms. The most important group is the polysaccharides including (i) microbial polysaccharides produced when various organic materials are added to soil and (ii) some of the polysaccharides associated with roots and the microbial biomass in the rhizosphere (Oades, 1978). Polysaccharides are produced rapidly (Haris et al., 1996) but are decomposed rapidly, and are associated with large (>250 µm diameter) transiently stable aggregates.

The polysaccharides bind together clay-sized particles into aggregates, which are of the order of 10 µm diameter. It is unlikely that small quantities of polymers with chain lengths of a few hundred angstroms would be important in binding particles into aggregates with diameters of several millimetres. However, polysaccharides stabilize aggregates less than 50 µm diameter, and perhaps also flocules of clay. This is in keeping with the, molecular size of exocellular polysaccharides and the size of the particles, which the polysaccharides glue together. Polysaccharides thus have less relative importance in soils with high organic matter contents, e.g., after many years of pasture growth.

(b) Temporary binding agents

Temporary binding agents are roots and hyphae, particularly vesicular-arbuscular (V A) mycorrhizal hyphae (Tisdall and Oades, 1979). Such binding agents build up in the soil within a few weeks or months as the root systems and associated hyphae grow. They persist for months or perhaps years and are affected by management of the soil (Tisdall and Oades 1979, 1980 a, b). The temporary binding agents are probably associated with macroaggregates and can be equated with the organic skeleton grains described by Bal (1973).

(i) Roots: Roots not only supply decomposable organic residues to soil and support a large microbial population in the rhizosphere, but roots of some plants, especially grasses, themselves act as binding agents, they appear to enmesh fine particles of soil into stable macroaggregates, even when the root has died.

Residues released into the soil by roots are in the form of fine lateral roots, root hairs, sloughed-off cells from the root-cap, dead cells, mucilages, lysates and volatile and water-soluble materials (Oades, 1978). The amount of organic carbon released by roots is related to the total length of root; Shamoot et al. (1968) found that, regardless of species, plants released 20-49 g organic material per 100 g harvested root. The root systems and associated fungal hyphae of pasture plants, especially grasses, are extensive and the upper layer of the soil under pasture is probably all rhizosphere, i.e. the roots are less than 3 mm apart (Barley,1970).

Part of the effect of plants on water-stable aggregates is also due to localized drying around roots (Allison, 1968). Electron micrographs of the rhizosphere show that particles of clay close to a root tend to be oriented almost parallel to the axis of the root; the percentage of oriented particles increases with the age of the root and with decreasing radial distance from the root. The particles of clay had probably been reoriented by the expanding roots and by localized drying around the roots, from randomly dispersed position to position of minimal energy.

Plants may also increase water-stable aggregation of soils indirectly by providing food for soil animals, such as earthworms and the mesofauna, enabling large populations to build up. Soil under 3-year-old pasture had few earthworms but after 8 years' pasture there were more than 1.5 x 10³ ha⁻¹. Earthworm casts generally contain more organic matter than the surrounding soil and the casts from soil under pasture were more stable than the surrounding soil. These earthworms may
stabilize structure by ingesting soil and mixing it intimately with humified organic materials in its gut (Greenland, 1965).

(ii) **Hyphae**: Temporary binding agents stabilize macroaggregates, i.e. >250 µm diameter (Tisdall and Oades, 1980b). This is probably because roots and fungal hyphae are relatively large and because they can grow in large pores in soil (Marshall, 1976), which in well-drained soils, are likely to contain air even during wet weather. Fungi have been shown to grow mainly in the outer parts of aggregates (Hattori, 1973). Most of the microbial filaments which have been reported to stabilize aggregates in the field in the presence of plants were probably VA mycorrhizal fungi (Tisdall and Oades, 1979). The water-stability of aggregates of a red-brown earth was related directly to the length of external hyphae of these fungi associated with unit weight of aggregates or soil.

(iii) **Saprophytic fungi**: Saprophytic fungi may also be included in temporary binding agents, since some of these sterile species could be isolated from soil in the field throughout the year (Warcup, 1967). This group includes dark-coloured fungi which tend to persist in soil for longer periods than hyaline fungi (Hurst and Wagner, 1969). These melanic fungi occur widely in soils (Warcup, 1967) but tend to be less conspicuous than sporing fungi so that their importance in aggregation may have been overlooked; yet Martin et al. (1959) showed that some melanic fungi stabilized aggregates as effectively as did hyaline fungi.

(iv) **Vesicular-arbuscular mycorrhizal fungi**: Vesicular-arbuscular mycorrhizal fungi, widespread in soils are obligate symbionts. Only recently have they been implicated in the water-stability of aggregates of soil. It is believed that VA mycorrhizal fungi tend to be most abundant in soils with low or unbalanced levels of nutrients: however, some plants are mycorrhizal even in fertile soils (Sanders et al., 1975). It is not known how long these fungi persist in soil once the host has died, but hyphae were still present in soil several months after the plants were killed although the hyphae may not have been viable (Tisdall and Oades, 1980a).

(v) **Other temporary binding agents**: Although fungi constitute more than 50 per cent of the microbial biomass in soil and probably contribute more than bacteria to the organic matter in soil, organic bonds probably develop also from degraded bacteria cells in the rhizosphere or around decaying organic residues (Foster, 1978), i.e. develop from bacterial cells which form transient binding agents.

In desert soils, filaments of blue-green algae formed a solid and mechanically, strong net which bound particles of soil or sand into a tough layer on the surface of the soil (Went and Stark, 1968). This layer may become leathery in water and even then may be difficult to break. Algae and lichens or algae and fungal hyphae may also form crusts in desert soils, which stabilize the soils against erosion (Shields et al., 1957).

(c) **Persistent binding agents**

Persistent binding agents consist of degraded, aromatic humic material associated with amorphous iron, aluminium and aluminosilicates to form the large organo-mineral fraction of soil which constitutes 52-98 per cent of the total organic matter in soils (Turchenek and Oades, 1978). The persistent binding agents probably include complexes of clay-polyvalent metal-organic matter, C-P-OM and (C-P-OM)x, both of which are <250 µm diameter, as described by Persistent binding agents are probably derived from the resistant fragments of roots, hyphae, bacteria cells and colonies (i.e. temporary binding agents) developed in the rhizosphere; the organic matter is believed to be the centre of the aggregate with particles of fine clay sorbed onto it (Foster, 1978) rather than the organic matter sorbed onto clay surfaces. However, persistent binding agents have not yet been defined chemically.
Also included in this group are strongly sorbed polymers such as some polysaccharides and organic materials stabilized by association with metals. Multifunctional organic anions associated with di- and trivalent metal cations will act as stabilizing agents, although as mentioned earlier, they may also aid dispersion.

**Effect of Agricultural Management on Soil Aggregation**

We need to understand how soil management influences aggregation so that we can make suitable modifications to farming practices to enhance soil structural stability. To choose which practices should be followed for ameliorating the soils, attention has to be paid to the level within the soil structural hierarchy requiring attention (i.e. macroaggregation or microaggregation). Tisdall and Oades (1982) suggested that water stability of macro-aggregates is dependent on the soil management, while water stability of micro-aggregates is independent of it. However, Watts et al. (1996) observed that soil management history influenced clay dispersibility.

**(a) Organic Matter Amendments**

Different strategies to manage SOM include: incorporation of crop residues, cover crop cultivation, addition of organic manures and application of organic wastes (sludge). These additions introduce a mixture of substrates into the soil where a heterogeneous microbial population starts decomposing them to produce biomass, CO$_2$ and secretions (Hadas et al., 1994).

Crop residues retained on or near the soil surface usually enhance infiltration by dissipating raindrop energy, thus minimizing aggregate breakdown and surface sealing, and by retarding surface water flow, thus providing more time for infiltration (Cassel et al., 1995). Straw left on top of the soil increased aggregate stability by reducing the wetting rate (Chan, 1995). Soil incorporated residues result in favorable infiltration when they maintain favorable soil porosity and organic-matter concentrations (Unger, 1992; Pikul and Zuzel, 1994). Loch (1994b) concluded that retention of crop residues on the soil surface has greater importance in improving water storage than improving soil aggregation. On the other hand, Baldo et al. (1994) reported that incorporation of wheat straw increased the stability of macro-aggregates but there was also a moderate tendency to increase dispersion of clay.

The amount, the C/N ratio of the residues and their decomposition rates influence the response pattern of soil structure (Sun et al., 1995). Addition of residues of cotton with high C/N ratio provoked immediate effect on the soil stability, but the effect was transient. Conversely, large amounts of residue with a moderate C/N ratio stabilize aggregates for longer periods (Hadas et al., 1994). Avnimelech and Cohen (1989) concluded that amendments with C/N ratios between 15 and 40 resulted in the greatest soil structural improvement. The soil water content and the N availability influence the residues’ decomposition rate and the effect on soil stability (Hadas et al., 1994). Although incorporation of crop residues have been seen as a practice to improve soil structural stability, in humid regions the excessive crop residues present problems for optimum crop establishment and plant growth (Carter, 1994).

Cover crops, such as grasses, legumes, and/or annual grain plants (barley or wheat), add C to the soil through root exudation and turnover and through decomposition of residues. In addition, legumes fix N (Roberson, 1991). Cover crops have rapid and significant effects on the stability of soil macro-aggregates, even when the total amount of organic C in the soil is apparently not affected (Roberson et al., 1991). They identified a rapid increase in heavy fraction (HF) carbohydrate content as a response to increases in C inputs by cover crops. Campbell et al. (1993b) found that legume green manure and hay crops reduced the wind-erodible fraction. Cover crops can also protect soil surface against the disruptive effect of water drops.

Organic manures also increase C and N, resulting in increased microbial biomass C and N (Amezeketa et al., 1996b). Weill et al. (1988) found that manure addition increased soil
macroaggregation. The fertilizer effect may be related to relative amount of roots produced, the associated root exudates and microbial growth.

Application of organic wastes (sludge and others) to soils increases the number and size of water-stable macro-aggregates (Lax and Garcia-Orenes, 1993). These authors suggest that fungi contribute more than bacteria to the increase in WSA after sludge application. The same authors agree that the dynamics of aggregation in a waste amended soil is characterized by two phases. In the first, "aggregative" phase, the labile part of the substrate is metabolized, and the resulting microbial activity is directly responsible for the formation of WSA. In the second, "stabilization" phase, while part of the organic cementing agents decompose, WSA also undergo stabilization processes, such as the binding of organic molecules to clay surfaces. Consequently, fewer but more stable aggregates remain.

**Crop Type and Crop Rotation**

Diverse plant species may contribute to soil aggregation in different ways, probably because of differences in root parameters (density, excretions, degree of mycorrhizal infection), in quality and quantity of organic matter input and/or in associated mesofaunal and microbial decomposers (Chan and Heenan, 1996).

Virgin soils have much higher aggregate stability than cultivated soils (Barzegar et al., 1994b). Aggregate stability varies greatly among different cropping systems. The presence of any crop in soils versus the fallow control was associated with increases in macro-aggregate stability (Monroe and Kladivko, 1987). A survey of the problems of soil degradation in agricultural soils in Quebec (Canada) showed that more than 80% of the soils under monoculture present signs of structural degradation relative to adjacent soils under perennial forages (Angers et al., 1993b). Kay et al. (1988) suggested that the decrease in aggregate stability following cultivation of a native or old-meadow soil may be very rapid, differing with soils and depending on the nature of soils constituents. Haynes et al. (1991) reported that increasing the duration of pasture increased the aggregate stability and soil organic carbon content whereas increasing the duration of arable crop decreased these values (Table 2). The soil resistance to slaking was increased in pastures and forage crops compared with arable soils (Haynes and Francis, 1993).

On the other hand, soil aggregate stability is also sensitive to the kind of crop grown, either as monoculture or in rotation with others (Table 3). Comparisons of water-stable macro-aggregates of soils under different crop rotations provide sometimes-contradictory results. Angers and Mehluys (1989) observed that the two years of cropping barley and alfalfa did not affect soil C and N contents but significantly increased carbohydrate content with respect to a fallow control. They concluded that at least part changes in water-stable aggregation ‘was related to carbohydrates in the soil. Angers et al. (1993b) obtained no effect on soil aggregation of two rotations (continuous barley vs. a 2-yr barley-red clover). Monroe and Kladivko (1987) did not find differences in macro-aggregate stability among different crops, such as corn, soybeans and wheat. Ellsworth et al. (1991) and Arrigo et al. (1993) reported lower stability under soybeans than under corn. Chan et al. (1994) found lupin more effective than wheat in promoting aggregation. Chan and Heenan (1996) found differences in structural stability among four crops in the order lupin> canola > barley> field pea. Miller and Radcliffe (1992) reported that legumes, because of their low C/N ratios and resulting fast decomposition rates, can stabilize soil aggregates rapidly. Gijssman and Thomas (1995) concluded that the addition of legumes to pastures did not affect the soil aggregate distribution, although aggregates showed somewhat more stability against slaking. Companion cropping has been other possible strategy to reduce erosion during alfalfa establishment. Companion cropping involves growing a small grain, typically oat, in association
with alfalfa during establishment. However, Wollenhaupt et al., (1995) did not find companion cropping very effective in reducing soil loss during alfalfa establishment.

In conclusion, the decreasing order of importance of different cropping systems on maintaining or increasing aggregate stability is the following: virgin soils > pasture and forage crops > arable crops in rotation > arable crops in monoculture > fallow.

Conclusions

From the above discussion it may be concluded that soil aggregation is not merely random assemblage of soil mass it involves a definite hierarchy. Maintaining high soil aggregate stability is a requisite for the sustainable use of soil and for the sustainable agriculture. The aggregate stabilization involves various physical, chemical and biological processes. The processes involved in the stability of microaggregation and macroaggregation are different. The microaggregates are stabilized against disruption by rapid wetting and mechanical disturbance, including cultivation, by several mechanisms in which organo-mineral complexes play a dominant role. Polysaccharides are also involved. The bindings of microaggregates appears to be relatively permanent and is not influenced by changes in the organic matter content of the soil caused by different management. On the other hand the water stability of macroaggregates depends largely on roots and hyphae, thus on growing root systems. Numbers of stable macroaggregates decline with organic matter content as the roots and hyphae are decomposed and are not replaced. The stabilization of macroaggregates is controlled by management, and is increased under pasture and declines when arable cropping is practiced.

References


Table 1: Models of aggregation and major stabilizing agents

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Stabilizing agent</th>
<th>Stage of aggregation (µm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfsol</td>
<td>Inorganic material, organic polymers, electrostatic bonds, coagulation</td>
<td>&lt; 0.2</td>
<td>Tisdall and Oades, 1982</td>
</tr>
<tr>
<td></td>
<td>Microbial and fungal debris</td>
<td>0.2 - 2 - &gt; 20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant and fungal debris</td>
<td>2 - 20 - &gt; 20 - 250</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roots and hyphae¹</td>
<td>20 – 250 - &gt;&gt; 2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polysaccharides²</td>
<td>20 – 250 &gt; 2000</td>
<td></td>
</tr>
<tr>
<td>Alfsol, Mollisol</td>
<td>Microbial debris, inorganic materials</td>
<td>&lt; 20</td>
<td>Oades and Waters, 1991</td>
</tr>
<tr>
<td></td>
<td>Plant debris</td>
<td>20 - &gt; 20 - 90</td>
<td></td>
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<tr>
<td></td>
<td>Plant fragments</td>
<td>90 - 250</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roots and hyphae</td>
<td>20 – 250 - &gt; 2000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 2000</td>
<td></td>
</tr>
<tr>
<td>Oxisol</td>
<td>Oxides</td>
<td>&lt; 20 - &gt;&gt; 250</td>
<td>Oades and Waters, 1991</td>
</tr>
<tr>
<td>Oxisol</td>
<td>Oxides</td>
<td>&lt; 2 - &gt; 100 - 500</td>
<td>Robert and Chenu, 1992</td>
</tr>
<tr>
<td>Vertisol</td>
<td>Organic matter</td>
<td>20 – 35 - &gt; 250</td>
<td>Collis-George and Lal, 1970</td>
</tr>
<tr>
<td>Andosols</td>
<td>Allophanes and amorphous aluminosilicates</td>
<td>0.001-0.01 - &gt; 0.1 - 1</td>
<td>Robert and Chenu, 1992</td>
</tr>
</tbody>
</table>

¹Soil with total organic carbon > 2%
²Soil with total organic carbon > 1%

Table 2- Effect of previous cropping history on aggregate stability, organic C, acid hydrolysable and hot water-extractable carbohydrate and biomass C content of a soil from the South Island of New Zealand

<table>
<thead>
<tr>
<th>Previous cropping history</th>
<th>Aggregate stability (MWD, mm)</th>
<th>Organic C (%)</th>
<th>Acid-hydrolysable carbohydrate</th>
<th>Hot water-extractable carbohydrate (µg C)</th>
<th>Microbial biomass C (µg C g⁻¹)</th>
</tr>
</thead>
</table>


The 1 year and 4 year pasture and year and 4 year arable soils come from a cropping rotation of 4 years arable followed by 4 years pasture. (Data from Haynes et al., 1991)

Table 3: The effect of plant species, grown in artificial aggregates of an alfisol, on root length, organic carbon and water-stable aggregates>250 µm diameter

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Root length ( (\text{cm cm}^{-3}) )</th>
<th>Organic carbon ( (% \text{ C}) )</th>
<th>% wsa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>-</td>
<td>1.25</td>
<td>31.4</td>
</tr>
<tr>
<td>Pea</td>
<td>3.9</td>
<td>1.51</td>
<td>49.5</td>
</tr>
<tr>
<td>Ryegrass</td>
<td>81.6</td>
<td>1.73</td>
<td>64.4</td>
</tr>
<tr>
<td>Wheat</td>
<td>27.8</td>
<td>1.54</td>
<td>55.6</td>
</tr>
</tbody>
</table>

(From Materechera et al., 1992)
Introduction

Land degradation is taking place globally and in all ecosystems; this brings severe consequences for our habitat, economy and well-being (UNCCD Report, 2009). Land degradation is a long-term decline in the productivity and function of the land from which it cannot recover unaided; this means a substantial, persistent loss of ecosystem services. The desertification means—land degradation in drylands but land degradation is not confined to drylands, it is a global issue. Over the last 25 years, some 25 per cent of the land has been degrading. Every year, more than 13 million hectares of forest (FAO 2005) and 5-6 million hectares of cropland were lost, and 20 million ha of farmland becomes unfit for crops or buried by urban and infrastructure development. About 146.82 million hectare area is reported to be suffering from various kinds of land degradation (NBSS&LUP). It includes water erosion 93.68 million ha., wind erosion 9.48 million ha., water logging/flooding 14.30 million ha., salinity/alkalinity 5.94 million ha., soil acidity 16.04 million ha. and complex problem 7.38 million ha. Unsustainable land use change namely intensive tillage practices, residue burning is responsible for at least a quarter of the excess carbon dioxide (CO₂) in the atmosphere - through the loss of soil organic carbon results in contributing to the greenhouse effect and global warming of the planet (Reicosky, 2003; Lal et al., 1995 and 1998). As we are producing more and more food per unit area without realizing the importance of soil health and quality.

At present, the atmospheric CO₂ concentration of 392 ppm, which is increasing at the rate of 2 ppm/year (Lal, 2008; Agarwal and Pathak, 2009) has resulted in unprecedented global warming (Fig 1. The 4x4 assessment of climate change scenarios for 2030s [through Regional Climate Model Had RM3-(Hadley Centre Regional Model Version 3) for A1B scenario] further confirms that the overall warming of all the region in India. The net increase in annual temperatures in 2030s with respect to 1970s ranges between 1.7°C – 2.2°C, with extreme temperatures increasing by 1-4°C, with maximum increase in coastal regions. The extreme maximum and minimum temperatures are also projected to increase in 2030s with respect to 2070s.

Further, this results in drastic change in rainfall patterns with erratic and high–intensity downpours and change in mean annual temperature; prolonged midseason dry spells are disastrous characteristics of the current monsoon trend (William Dar, 2009). Because of the rise of such situations, farmers’ are facing difficulties in having at least one good harvest either in the kharif or rabi crop season. Farming in the arid and semi-arid regions is mainly dependent on the south– west monsoon rain. Mean annual rainfall of the region that varies from 700 mm to 1300 mm necessitates various cropping patterns across the rainfed region. Development of cropping systems that are resilient to these climatic extremes as well as sustained soil quality and productivity has been, and continues to be, a major challenge to farmers/scientists/researchers in the rainfed region.
Of-late, conservation agriculture (CA) has been realized has a potential practices to revitalize the degraded (soil) resource base as well climate change mitigation in Rainfed regions of India. In this paper, an attempt has been made to provide broad overview on conservation agriculture with special emphasis to revitalizing degraded resource base/climate change mitigation.

**Need for Conservation Agriculture for revitalizing degraded resource base**

India rejoices in achieving the highest ever estimated foodgrain production of 250 million tones (Mt) during 2011–2012, which is about 9 Mt higher than previous year’s production (241 Mt) and also surpasses all the previous years’ records. Notwithstanding this jubilant mood, we need to produce about 40 Mt additional food grains by 2020 to meet the population demand. On the other hand, the world is facing a crisis–like situation for staple foodgrains especially rice and wheat due to a paradigm shift from food crops to energy- and/or bio-fuel plants. Soil and water management form the basis for sustainable system of productive agriculture. As these natural resources are deteriorating/declining at a fast rate, it necessitates the need of conservation agriculture to restore soil quality, enriching soil organic carbon (SOC) and also feeding the projected population of India of about 1.48 billion by 2030.

**Conservation Agriculture**

Conservation agriculture (CA), aims at a system of raising crops in rotation without tilling the soil while retaining crop residues in the soil surface (Abrol and Sunita, 2006; http://www.conserveagri.org) that has three key principles:

1. Minimum (mechanical) soil disturbance
2. Maximum (permanent) soil cover/residues
3. Appropriate (diversified) crop sequence/rotation

The three CA principles are by no means new, these are well known as resource conserving technologies. The important new feature of CA is the simultaneous and permanent application of all three principles. Conventional practices like residue burning, intensive tillage practices, over exploitation soil resource results in loss of SOC which further lead to irreversible land degradation. Unlike conventional practices, conservation agricultural practices like zero-till/minimum tillage along with residue on the soil surface helps in increasing carbon deposits into the soil and reversing the trend of conventional agriculture (Fig. 2).

![Fig 2. Transition of Conventional agriculture to Conservation Agriculture](http://www.conserveagri.org)
Climate change models predict drastic change in/ decreased rainfall and climatic extremes in many of the world’s cropping regions and, as a result, substantial land area devoted to rainfed agriculture is likely to become less productive unless there are major changes in the geographical locations where major crops are grown. Such reduction in productivity may be minimized by novel crop management techniques and introduction of improved genotypes with enhanced resilience to abiotic stresses. If CA is adopted in a comprehensive way, over a period of time it will brings multiple benefits that minimizes soil loss, conserve water, control weeds enrich SOC and increase productivity in the face of challenges facing the agriculture sector (Abrol and, Sunita 2005). The various benefits are reduced cost of cultivation, enhanced efficiency of applied nutrients and water resulting from physical, chemical and biological improvement in soil, enhanced carbon sequestration and buildup of soil organic matter (SOM) with mitigation of greenhouse gases (GHGs) emissions.

**Conservation tillage**

‘Conservation tillage’ is often defined as any tillage system that leaves enough crop residues (30%) on field after harvest to protect the soil from ranging from no-tillage to intensive tillage depending on soil conditions. Conservation tillage evolved from practices that range from reducing the number of trips over the field to raising crops without any primary or secondary tillage. Current emphasis is on leaving crop residues

<table>
<thead>
<tr>
<th>Tillage systems</th>
<th>Descriptions (Conservation tillage Information Center, 2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-tillage/ No-Tillage (NT)</td>
<td>It is a form of conservation tillage, have been used for thousand years of indigenous cultures simply because humans did not have manual force to till a significant area. Soil is left undisturbed from planting harvest except for nutrient injection. Planting or drilling is accomplished in a narrow seed-bed by zero-tillers. Weed control is accomplished primarily herbicides. Cultivation may be used for emergency weed control.</td>
</tr>
<tr>
<td>Mulch Tillage</td>
<td>The Soil is disturbed prior to planting. Tillage tools such as chisels, field cultivators, disks, sweeps, or blades are used. Weed control is accomplished with herbicides, cultivation or both.</td>
</tr>
<tr>
<td>Reduced Tillage</td>
<td>Full width tillage involving one or more tillage trips leaving residue retained (15-30%) on the field. Reducing tillage operations/ trips when compared to conventional systems.</td>
</tr>
<tr>
<td>Conventional Tillage</td>
<td>Tillage types that leaves less than 15% residue cover after planting critical wind/water erosion period. Generally includes ploughing or other intensive tillage operations; residue removed/burning during cultivation. Weed control is accomplished with herbicides, cultivation or both.</td>
</tr>
</tbody>
</table>

**Status of Conservation Agriculture**

The 4th World Conservation Agriculture Congress (4th WCCA) held in New Delhi during 4–7th February 2009, brought both national and international attention to the desperate importance of Conservation agriculture. The Millenium Development Goals (MDG) stress upon reducing hungry populations, although the number of starving people is increasing, land available per person is decreasing and demand for food is increasing. There are also signs of soil fatigue in some places as the productivity factor declines. The big question is how to produce additional food to meet the growing demand in the population. At the same time, profits of small farm holdings need to be maintained, which can be achieved only through CA.

**CA- International status**
According to recent estimates, the extent of no-tillage (CA) worldwide is more than 105 million hectares (Derpsch and Friedrich, 2009). On the global scale, no-tillage is almost exclusively a large or medium-sized farm domain. Of the cropped area, no-till has been practiced on 46.8% (49.5 Mha) in South America, in which Brazil is the leader with 22 million hectares or 45 per cent of its total cultivated land under CA (Derpsch and Friedrich, 2009). About 38% (40 Mha) of no-tillage is practised in the USA and Canada, and 11.5% in (12 Mha) in Australia and New Zealand: with less than 4% of no-tillage in the rest of the world—including South Asia, East and SE Asia, Africa, and Europe (Dennis Garrity, 2008; http://www.worldagroforestry.org/af/node/213).

CA- National Status

In India, efforts to adopt and promote resource conservation technologies have been under way for nearly a decade. Of late, these technologies are finding acceptance by the farmers. The Rice-Wheat Consortium for IGP (by CGIAR and NARS) has brought national attention to adopting conservation agriculture. This system has pronounced effects on mitigation of GHG emission and adaptation to climate change. Adoption of conservation agriculture has expanded to cover about 2–3 M ha (RWC, (2005); Gupta et al., 2005; Grover and Sharma (2007); WCCA Report 2009) there is a scope for intensifying CA with good results in the region like north–western and central India. Another estimate reported just about 2 Mha are under this agriculture in India, which rests on conserving precious resources such as water, diesel, labour and protection of land from degradation. If the total land under conservation agriculture reaches 3.5 Mha, the saving in diesel alone would be 120 million litres (Joshi, 2008, In Business line).

Benefits of CA

CA in the arid and semi-arid regions of India has to be understood in a broader perspective. Conservation tillage is more appropriate under rainfed agriculture than zero tillage. Practice of CA has to be adopted holistically so that it minimizes soil loss, conserves water and controls weeds, which is essential for successful crop production under rainfed conditions. (Venkateswarlu et al., 2009). If CA is adapted and adopted in a broad way, over a period of time brings multiple benefits in the face of challenges facing the agricultural sector (Abrol and Sunita, 2005) as well as it will helps in revitalize/rejuvenate the degraded resource base over a period of time.

The various benefits are listed below:

- Short–term: Reduced cost of cultivation
- Medium–term: (3–5 yrs) enhanced efficiency of applied nutrients and water that result from physical, chemical and biological conditions.
- Long–term: Enhanced C sequestration and build-up of SOM which mitigate GHGs emissions.

Resource Conservation Technologies (RCT)

Off late to promote CA, recent research efforts have attempted to develop alternate tillage and crop establishment techniques, termed as resource conservation technology (RCT), which are more efficient, use of less inputs, and improve production and income compared to conventional practices (Aggarwal and Pathak, 2009). The Potential benefits on the key-Resource Conservation Technology (RCTs) in terms of climate change mitigation and adaptation relative to conventional practices are given below.

<table>
<thead>
<tr>
<th>Resource Technology</th>
<th>conserving</th>
<th>Potentials benefits relative to conventional practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Tillage</td>
<td></td>
<td>Reduced water use, C-sequestration, increased yield and income, reduced fuel consumption and GHG emission.</td>
</tr>
</tbody>
</table>
Laser-aided land leveling  Reduced water use, fuel consumption, GHG emission
Direct drill seeding rice Less requirement of water, saves time, post harvest condition of field is better for succeeding crop, deeper root growth
Diversification Efficient use of water, increased income, increased nutritional security, conserved soil fertility, reduced risk
Raised bed planting Less water use, improved drainage, better residue management, more tolerant to water stress.
Leaf colour chart Reduces N fertilizer requirement, reduces N loss and environmental pollution, reduces nitrous oxide emission.


Residue Burning: A nuisance or panacea to the Farmers

India produces about 500 million tons (Mt) of crop residues annually. These residues are used as animal feed, composting, thatching for rural homes and fuel for domestic and industrial use. However, a large portion of the residues, about 140 Mt, is burned in field primarily to clear the field from straw and stubble after the harvest of the preceding crop. There is a large variability in crop residues generation and their use depending on the cropping intensity, productivity and crops grown in different states of India. Residue generation is highest in Uttar Pradesh (60 Mt) followed by Punjab (51 Mt) and Maharashtra (46 Mt). Among different crops, cereals come first with 352 Mt residue generation (Source: Ministry of New and Renewable Energy (MNRE 2009), Govt. of India).

Traditionally crop residues have numerous uses such as animal feed, fodder, fuel, roof thatching, packaging and composting. Cereal residues are mainly used as cattle feed. Rice straw and husk is used as domestic fuel or in boilers for parboiling rice in states like West Bengal and Tamil Nadu. The uses for various residues are different in different states.

In general, Crop residues serve a number of beneficial functions, including soil surface protection from erosion, water conservation and maintenance of soil organic matter (OM). Large amounts of residue in the soil surface have traditionally been viewed as a nuisance, and have been associated with mechanical planting difficulties, poor crop-stand establishment, decreased efficacy of herbicides, release of growth-inhibiting allelopathic compounds, and ultimately, yield reductions. Therefore, crop residues, particularly wheat residue, are commonly burned or plowed under followed by discing to prepare a seedbed for double-cropped soybean (Prasad et al., 1999).

Worldwide, many farmers conduct burning of field crop residue for a variety of real and perceived benefits, such as timeliness of field operations, reduced cost associated with residue management, increased crop yield and better control of weeds and diseases (Chen et al., 2005). However, causes considerable loss of organic C, N and other nutrients by volatilization as well as detrimental effect to soil microorganisms. In comparison to burning, residue retention increases soil carbon and nitrogen stocks provides organic matter necessary for soil macro-aggregate formation (Six et al., 2000) and fosters cellulose–decomposing fungi, and thereby, carbon cycling. Residue burning is a prevalent practice in many parts especially in the rainfed region as it causes a lot of impediment during field operations (Fig 3a & b). It is a quick, labour-saving practice to remove residue that is viewed as a nuisance by farmers. However, residue burning has several adverse environmental and ecological impacts. The burning of dead plant material adds a considerable amount of CO₂ and particulate matter to the atmosphere and can reduce the return of much needed C and other nutrients to the soil (Prasad et al., 1999). The lack of a soil surface cover may also increase the loss of soil minerals via surface runoff/soil erosion. Crop residues returned to the soil maintain OM levels, and crop residues also provide substrates for soil microorganisms. As microbes use or decompose crop residues and soil OM, CO₂ is given off as a by-product of soil
respiration. Therefore, it is reasonable to believe that residue levels might affect soil surface CO₂ fluxes.

**Fig 3a Impediments in field operations**  
**Fig 3b Charred view of residue in field**

**Crop residue management for Climate Change Mitigation**

The main threat to soil resource is soil erosion, loss of organic matter (OM), soil compaction, soil sealing etc. It has been realized worldwide that crop residue retention through conservation agriculture (CA) is able to revert these soil degradation. As the food demand is ever increasing due to population explosion coupled with spiral of fertilizer prize and declining in native mineral sources has forced us to rethink – reuse the crop residues left in the field. Rice–Wheat and Soybean–Wheat are the dominant cropping system in many parts of our country, where the residue left on the field during harvesting of wheat poses serious impediment to the next crop as well as greater challenge to the farmers to recycle them. One of the easiest and quickest ways to remove the residue is ‘burning’. Thus, residue burning is a prevalent practice in many parts of the country. By and large, soil application of crop residue either used as mulch on soil surface or incorporation of raw residue or mixing of burnt ashes.

Microbial and root activities dominantly influenced by soil moisture and temperature. Environmental fluctuations of temperature and moisture are in turn affected by residue management practices, such as burning and tillage.

- For example, burning removes residue and the insulating effect of a residue cover on the soil surface causing temperatures to increase, which can stimulate microbial activity and soil respiration, and enhanced fluctuations in soil moisture and temperature.
- Managing crop residues by burning also removes the evaporation barrier the residue provides causing the soil to dry out quickly; thus also affecting microbial activity and soil respiration.
- Agricultural soils can however actually serve as a significant C sink, rather than a C source, at least until the maximum capacity to store C is achieved, if improved residue management and reduced tillage systems are adopted.
- Therefore, alternative residue management options must be developed to minimize or eliminate the tradition of residue burning and thereby reduce soil respiration.
The study conducted at IISS, Bhopal and JNKVV, Jabalpur gave encouraging results for residue retention against the residue burning under the conventional practices.

Wheat residue incorporation or retention coupled with application of 28 kg N ha\(^{-1}\) through fertilizer or organic manures is more beneficial than burning in terms of enhanced crop productivity and soil fertility. Wheat residue incorporation resulted in 20–22% higher yields in soybean and 15-25% in wheat as compared to residue burning. Soil incorporation of wheat residue plus N supplementation through FYM at the rate of 28 kg N ha\(^{-1}\) (approx. 4 t FYM ha\(^{-1}\)) along with 25 kg P ha\(^{-1}\) for rainfed soybean and 68 kg N + 30 kg P ha\(^{-1}\) for irrigated (1+ 2 irrigations) wheat was more effective and profitable (Subba Rao \textit{et al}. 2009). In another long-term tillage experiment showed that residue retention for more than 6-7 years recorded encouraging results compared to conventional system.

A long–term experiment (10 years) was conducted in rice–wheat in Vertisols (Jabalpur). The results indicate that in (rice–wheat) both the crops adoption of no-tillage had a slight advantage in terms of yield as compared to conventionally tilled plots. Deep tillage did not benefit either of the crop yields compared to conventional tillage. Similarly, straw mulch application at the rate of 5 t/ha was found highly effective in further improving yield. With the adoption of CA, the beneficial effects are likely to increase over time due to improvement in soil quality (Tomar, 2008).

In another conservation agriculture experiment conducted by Somasundaram (unpublished data) reported that various cropping systems had clear effect on leaf litter addition to the soil and also on crack volume. Among the various cropping systems compared, soybean + pigeon pea (2:1) recorded highest leaf litter addition followed by soybean+ cotton (2:1) and soybean-wheat systems. Maize–gram system recorded the highest crack volume among the six cropping systems compared. Reduced tillage (RT) recorded higher leaf fall/crop residue addition than conventional tillage system. After completion of first crop-cycle soil samples were collected and analyzed for soil organic carbon content. The results showed that the SOC was higher in surface layer (0-15cm) than the sub-surface (15-30cm) under both tillage systems. Irrespective of soil depth, SOC was found to be more under reduced tillage (RT) compared to conventional tillage (CT) system. However, significant difference was observed only under soybean cropping system at 0-15cm depth. From the weed biomass data, it was inferred that among the soybean based cropping systems studied, soybean+ cotton (2:1) recorded significantly higher weed biomass as compared to other systems. However, maize–gram recorded higher weed biomass than soybean based cropping systems. Although, population of broad leaved weeds were less under reduced tillage (RT) due to herbicide spray, grassy weeds were found to be more.

**Tillage –Crop rotation–Carbon sequestration**

The Intergovernmental Panel on Climate Change (IPCC) determined that agriculture was directly responsible for approximately 20% of the annual anthropogenic emissions of greenhouse gases (IPCC, 1995). Agricultural soils can however actually serve as a significant C sink, rather than a C source, at least until the maximum capacity to store C is achieved, if improved residue management and reduced tillage systems are adopted (Paustian \textit{et al}.., 2000). Therefore, alternative residue management options must be developed to minimize or eliminate the tradition of residue burning and thereby reduce soil respiration.

Conventional agriculture is normally based on soil tillage done through ploughing. Soil tillage has in the past been associated with increased fertility by improving the mineralization process, which results in loss of soil organic matter in the long run. Tillage mixes and loosens the soil and has also been shown to stimulate microbial activity, OM oxidation and soil respiration. Moreover, it has been recognized that frequent disturbance of soils leads to detrimental effects. Furthermore, tillage is increasingly becoming costlier for farmers and may account for 20% or
more of the total crop production costs depending on crop and soil type. In order to keep farming a remunerative enterprise, farmers have to reduce production costs and improve productivity.

Double-cropping systems have become prevalent in the central India due to an increased profit margin that can be achieved from maximizing agricultural use of the land. The best epitome of this statement is soybean following wheat during rabi season that always remains a profitable venture in the region and in many parts of the country. However, a successful soybean–wheat rotation is contingent on wheat residue management practices used before sowing soybean crop in the subsequent rotation. For example, burning removes residue and the insulating effect of a residue cover on the soil surface causing temperatures to increase, which can stimulate microbial activity and soil respiration, and enhanced fluctuations in soil moisture and temperature. Managing crop residues by burning also removes the evaporation barrier the residue provides causing the soil to dry out quickly; thus also affecting microbial activity and soil respiration.

On the other hand, increased carbon accumulation (sequestration) though recycling of organic residues is not only increased the nutrient supply and turnover capacity of soils but also resulted in significant changes in the physical and biological properties of the soils. As a result, there was an increase in the water holding capacity of soils and ability to withstand longer dry spells during crop growing period. Alternate cropping sequence is very important for maintaining soil fertility in the rainfed region.

**Adoption and Impact of CA in rainfed region**

Conservation agriculture (CA) is yet to go from experimental plots/research stations to farmers’ fields. Of late, CA is gaining momentum in terms of some experimental results and also by some initiatives made by Professional Alliance for Conservation Agriculture (PACA) and Centre for Advancement of Sustainable Agriculture (CASA). Besides this, adoption of CA in these areas/regions is very low. Black vertisols and associated soils occupy 73 Mha (22.5% of the total geographical area) in sub-humid and semi-arid tropics of India, out of which more than 60 m ha are spread in Maharashtra, Madhya Pradesh, Gujarat, Rajasthan, northern parts of Karnataka and Tamil Nadu. Madhya Pradesh (MP) is known for its numerous river basins and is spread over about 30.7 m ha, out of which nearly 50 per cent is cultivable/arable. In spite of numerous rivers and river basins in the state only 20% of the agricultural area is under some form of irrigation. Farming in the state is mainly dependent on the south–east monsoon rain. The mean annual rainfall shows wide variation and varied from 700 mm in the west to 1300 mm in the east, necessitating varied cropping patterns across the state. On one hand there is development of cropping systems that are resilient to these climatic extremes and on the other suitable farm equipment for zero-tillage practices and its adaptability and residue management have been a greater challenge to the region.

Soybean–wheat is the dominant cropping system in MP, where the residue left on the field during harvesting of wheat poses serious impediment to the next crop as well as greater challenge to the farmers to recycle them. One of the easiest ways to remove the residue is burning. Thus, residue burning is a prevalent practice in many parts especially in Bhopal, Harda, Khandwa, Guna and Chhindwara districts of MP. In recent past, CA is gaining momentum in terms of some experimental results and also by some initiatives made by PACA and CASA. However, adoption of CA in these areas/regions is very low due to the mindset/attitudinal change and non-availability of farm equipment to small and marginal farmers.

Sharma et al. (2009) reported significant effects (8 years) of tillage as well as conjunctive nutrient–use treatments on sorghum and mung bean grain yields at Hyderabad. Conventional tillage up to the eighth year of the study maintained 12.8 and 11.2% higher sorghum and mung bean grain yields, respectively, compared to reduced tillage. After eight years, reduced tillage tended to be equal or better than conventional tillage in improving crop yields. Energy saving data
showed that conservation tillage could save about 20 litres of diesel and 187,331 kcal of energy ha$^{-1}$ over the conventional system. This raised the hope of success of reduced tillage in these SAT Alfisols, if practised over a long-term.

Long-term impact of conservation tillage practices on soil properties of Vertisols were studied under soybean–wheat system in Bhopal. Conservation tillage practices that is, no-tillage (with crop residues retained on the surface and direct drilling of seed) and reduced tillage (residue retained + one sweep tillage) were as effective as conventional tillage (residue removed + one summer tillage by sweep cultivator + two tillage by sweep cultivator) in terms of crop productivity under soybean and wheat. (Hati et al., 2009). Wheat residue incorporation or retention coupled with application of 28 kg N ha$^{-1}$ through fertilizer or organic manures (~4 t FYM ha$^{-1}$) is more beneficial than burning in terms of enhanced crop productivity and soil fertility. Wheat residue incorporation resulted in 20–22% higher yields in soybean and 15–25% in wheat as compared to residue burning (Subba Rao et al., 2009). Temporal changes on soil water storage were studied under conservation tillage in soybean at IISS, Bhopal. In the early stage of the crop, moisture content in the profile was more in MB and conventional tillage followed by reduced tillage and no-till treatments due to more infiltration rate. In later stage profile moisture storage was higher in RT and NT compared to CT and MB due to the presence of residues and bio-pores and less disturbance of surface soil in conservation tillage.

Conclusions

- CA programme will bring various key stakeholders through a project based system/farming based approach. Simultaneous and permanent application of all three principles of CA help in synergy effects which enforce the effect of single practice while eliminating the disadvantages of each technology applied in isolation (CA Newsletter, 2008). Such permanent application leads to a long term change in the agro-ecosystem and makes the production system increasingly resilient to external factors, increasing the parameters of sustainability of the production systems.
- There is considerable scope for increasing rabi cropping (in rainfed region) on residual moisture provided more effective in-situ moisture conservation techniques are adopted and matching the improved cultivars.
- CA component should be included in soil health card/smart card for proper monitoring of crop residue retention/burning.
- Familiarization of CA technologies at each KVK and state agricultural departments–awareness and dissemination of these technologies at block level through attractive CA–demonstration.
- Alternative residue management options (depth of incorporation, optimum size of residue for faster decomposition when it is incorporated in soil) must be developed to minimize or eliminate the tradition of residue burning and thereby reduce soil respiration, increase soil organic carbon and improve soil health.
- Like water conservation principles–‘catch the water where it falls’, forcrop residues–‘recycle the crop residue where it comes’ (excluding livestock and domestic use by the farmer).
- There is a need for modification of harvesting equipments for spreading and incorporation of residues uniformly across the field while harvesting of crops as well as creating better seed-bed for succeeding crops.
- Residue retention based–incentives to farmers for at least minimum 3–4 years similar to organic farming. Changing agricultural practices can be risky to farmers, and therefore, creation of incentives, policies and legislation is need of the hour.
- The adoption of conservation agriculture practices for a period of time is not only able to sequester soil organic carbon but also holds scope for improvement in soil quality and crop
productivity thereby promoting sustainable production despite of anticipated change in the climate (mitigation of climate change).

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Ministry of New and Renewable Energy (MNRE 2009), Govt. of India


Introduction

The C stored in soils is mainly in form of organic matter. SOC content is highly dynamic affected by ecological drivers (e.g., climate, vegetation, and anthropogenic activity), soil environmental factors (e.g., temperature, moisture, pH, redox potential, and substrate concentration gradients), and biochemical or geochemical reactions (e.g., decomposition, assimilation, leaching etc.) (Li, 2000, 2001; Li et al., 2004). Soil organic carbon (SOC) have received attention in past few years in terms of the potential role they can play in mitigating the effect of elevated atmospheric CO2. Process-based soil organic C (SOC) models are widely used for simulating, monitoring, and verifying soil C change (Basso et al. 2011). Soil organic matter (SOM) turnover models are very effective at simulating changes in SOM associated with different agricultural management systems or with climatic changes. Among the existing SOM models, the Denitrification-Decomposition (DNDC) model developed by Li et al. (1992) has been widely used for simulation of soil carbon dynamics. The DNDC model is a process-base model of carbon (C) and nitrogen (N) biogeochemistry in agricultural ecosystems. The entire model is driven by four primary ecological drivers, namely climate, soil, vegetation, and management practices. It is inherently important for a successful simulation to obtain adequate and accurate input data about the four primary drivers. The Denitrification-Decomposition (DNDC) model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems.

As described in detail by Li et al. (1992, 1994, 2000, 2003), and in the user’s guide, the DNDC model consists of two components. The first component, consisting of the soil climate, crop growth and decomposition sub-models, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles driven by ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts emissions of carbon dioxide (CO2), methane (CH4), ammonia (NH3), nitric oxide (NO), nitrous oxide (N2O) and dinitrogen (N2) from the plant-soil systems. The entire model forms a bridge between the C and N biogeochemical cycles and the primary ecological drivers (Li et al. 1992, 1994; Li 2000).

Input files required for DNDC model initiation

Climate
Minimum- daily mean air temperature (in °C) daily rainfall (in mm)
Optional- daily minimum air temperature (in °C) daily maximum air temperature (in °C) solar radiation (MJ m² day⁻¹) wind speed

Soil
Minimum- land use type (upland crop field, rice paddy field, moist grassland/pasture, dry grassland/pasture, pristine wetland) soil texture (sand, loamy sand, sandy loam silt loam, loam, sandy clay loam, silty clay loam, clay loam, sandy clay, silty clay, clay, organic soil) bulk density (in g/cm³) soil pH field capacity (water filled pore space, 0-1) wilting point (water filled pore space, 0-1) clay fraction (in %, 0-1) hydraulic conductivity (in cm min⁻¹) soil organic carbon (in kg C kg⁻¹) NH₄⁺ and NO₃⁻ concentrations (in mg N kg⁻¹) slope (in %) microbial activity index (0-1)
Optional-SOC partitioning (in %, into very labile litter, labile litter, resistant litter, humads and humus)

Management
Crop
Minimum - crops per year crop type default maximum biomass production (kg dry matter ha\(^{-1}\)) planting date harvest date Fraction of leaves and stems left in the field (in %)
Optional - initial biomass (kg dry matter ha\(^{-1}\)) initial photosynthesis efficiency maximum photosynthesis rate (in kg CO\(_2\) ha\(^{-1}\) hr\(^{-1}\)) development rate in vegetative state development rate in reproductive state

**Tillage**
Number of applications per year tilling date tilling method (mulching, ploughing slightly, ploughing with disk or chisel, ploughing with mouldboard)

**Fertilisation**
Minimum-number of applications per year fertiliser date fertiliser type (urea, anhydrous ammonia, ammonia bicarbonate, NH\(_4\)NO\(_3\), (NH\(_4\)\(_2\))SO\(_4\), Nitrate, (NH\(_4\))\(_2\)HPO\(_4\)) fertiliser amount
Optional-release control nitrification inhibition

**Manure amendment**
Number of applications per year fertilizer date manure type (farmyard manure, green manure, straw, slurry animal waste, compost) manure amount

**Weeding**
Weeding problem (not existing, moderate, serious) number of applications per year weeding date

**Flooding**
Number of times per year starting date end date water leaking rate flood water pH

**Irrigation**
Number of irrigation events per year irrigation date irrigation amount irrigation water pH

**Grassland**
Number of grazing and/or cuttings starting date (grazing) end date (grazing) application date (cutting)

**An example of data input required for DNDC simulation**

<table>
<thead>
<tr>
<th>Site name</th>
<th>Jabalpur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude (N)</td>
<td>...............</td>
</tr>
<tr>
<td>Longitude (E)</td>
<td>...............</td>
</tr>
<tr>
<td>Soil name</td>
<td>Black soil</td>
</tr>
<tr>
<td>Experimental period (years)</td>
<td>1980-2000</td>
</tr>
<tr>
<td>Topsoil depth (cm)</td>
<td>100</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>52</td>
</tr>
<tr>
<td>Bulk density (Mg m(^{-1}))</td>
<td>1.30</td>
</tr>
<tr>
<td>PH</td>
<td>7.6</td>
</tr>
<tr>
<td>Initial topsoil SOC (g kg(^{-1}))</td>
<td>10.0</td>
</tr>
</tbody>
</table>

**Kharif crop** Soybean
Sowing date | 6/25(6/20-6/30)
Tillage date | 6/12 6/8-6/20)
Total N applied (kg ha\(^{-1}\)) | 20 (20-0)
Harvest date | 9/25 (9/15-9/25)

**Rabi crop** Wheat
Planting date | 11/15 (11/10-11/20)
Harvesting date | 3/30 (3/25-4/05)
Tillage date | 09/20, 10/05, 10/11
Total N applied (kg ha\(^{-1}\)) | 120
Number of N application times | 3
Date of straw application | no
Amount of straw applied (kg C ha\(^{-1}\)) | no
**DNDC model validation**

DNDC consists of six sub-models, which simulate soil climate, plant growth, decomposition, nitrification, denitrification and fermentation, respectively. The six sub-models interact to enable DNDC to simulate a relatively complete suite of biochemical and geochemical processes occurring under both aerobic and anaerobic conditions. DNDC simulates SOC dynamics by tracking the turnover of four SOC pools, namely plant residue (or litter), microbial biomass, humads (or active humus), and passive humus. Each pool consists of two or three sub-pools with specific decomposition rates subject to temperature, moisture, redox potential and N availability in the soil. As soon as fresh crop residue is incorporated into the soil, DNDC will partition the residue into very labile, labile and resistant litter pools based on C/N ratio of the residue. The lower the C/N ratio, the more of the residue will be partitioned into very labile or labile pool. Each of the SOM pools has a specific decomposition rate subject to temperature, moisture and N availability. The organic matter in the litter pools will be broken down by the soil microbes. When the microbes die, their biomass will turn into humads pool. Humads can be further utilized by the soil microbes and turned into passive humus. During the sequential decomposition processes, a part of the organic C becomes CO$_2$, and a part of the organic N becomes ammonium (Adapted from Zhang et al., 2006).

**Implications related to model initiation**

Simulation accuracy of global biogeochemical carbon model depends on the initial carbon content of soil and their relative distribution of soil carbon pools. No definite method of quantification of soil carbon pools differentiation has been proposed by the model developer. Basso et al. (2011) developed iterative procedure for computation of soil carbon pools for initialization of DSSAT-Century model. Predicted changes in SOC should also be compared with measured data that represent the spatial and temporal range of model inferences to assess uncertainty and bias (Falloon and Smith, 2003; Ogle et al., 2007). The availability of reliable measurements of total SOC may not be sufficient to properly initialize soil C models. Depending on the partitioning of soil C into the different pools, decomposition of SOC during a growing season may result in very low or very rapid rates of mineralization and supply of nutrients. Thus, for the same initial total SOC value, the model may simulate vastly different yields under identical environmental and management conditions depending on how the SOC is partitioned into different pools (Basso et al., 2011). The inappropriate initialization of SOC pools can also lead to inaccurate assessment of inter-annual variability (Yeluripati et al., 2009). Typical values of the C fractions in each pool may be provided by model developers, but caution should be used because such information may prove to be unreliable for the soil and cropping system being simulated (Basso et al, 2011). In DNDC model, the model assumes default value for fraction of soil organic carbon in litter, humad and humas (active, slow and resistant pool) irrespective of soil texture class.

**References**


14. Soil carbon sequestration and land use change: prospect and potential

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What is Soil Carbon Sequestration?

Sink of carbon from atmosphere to either plant into soil or from atmosphere into soil is called as soil carbon sequestration. Excluding carbonate rocks (inorganic carbon path), a soil represents the largest terrestrial stock of carbon, holding 1500 Pg \((1 \text{Pg} = 10^{15} \text{ g})\), which is approximately twice the amount held in the atmosphere and three times the amount held in terrestrial vegetation. Soil inorganic carbon (SIC) pool contains 750 - 950 Pg C. Terrestrial vegetation is reported to contain 600 Pg C. The majority of carbon is held in the form of soil organic carbon, having a major influence on soil structure, water holding capacity, cation exchange capacity, the soil’s ability to form complexes with metal ions to store nutrients, improve productivity, minimize soil erosion etc. This organic carbon is highly sensitive to changes in land use and management practices such as increased tillage, cropping systems, fertilization etc., leading to soil organic carbon decline.

Impact of Land use and management practices on SOC storage

In general, soils with high SOC pool have more biomass productivity than those with low SOC pool. High biomass productivity from soils of high SOC pool is attributed to high soil aggregation and better soil tilth, high plant-available water retention capacity, more resistance to erosive forces of water and wind, and lower compaction ability. Enhancement of SOC pool reduces leaching losses of fertilizers and pesticides, and losses of chemicals in surface run–off also decrease with increase in SOC pool. Thus, increasing SOC pool improves quality of both soil and water resources. Land use and soil management systems, which enhance the amount of biomass returned to the soil, also accentuate the terrestrial C pool. Different technological options for biotic and soil C sequestration include afforestation, and restoration of degraded ecosystem, establishment of bio-energy plantations with a large potential for biomass production, establishing perennials with a deep and prolific root system, growing species containing high cellulose and other resistant species containing high cellulose, and developing appropriate land use systems. Similarly, strategies for soil C sequestration include adoption of conservation tillage and mulch farming techniques, maintenance of soil fertility, soil and water conservation, and adoption of complex rotations. The total potential of SOC sequestration through restoration of degraded soils in India is \(10-14 \text{Tg C yr}^{-1}\).

Major changes in land use occurred in the forests and grassland with 39.9 and 37.5 % of total land use change (Lal et al, 1999). Change in land use contributes C to the atmosphere in two principal ways: (i) release of C in the biomass which is either burnt or decomposed, and (ii) release of SOC following cultivation enhanced mineralization brought about by change in soil moisture and temperature regimes and low rate of return of biomass to the soil. Carbon contained in the biomass of the climax vegetation is in the order: tropical rainforest > temperate forest > temperate deciduous > boreal forest > tropical woodland > temperate woodland > tropical grassland > temperate grassland > desert scrub > tundra and alpine meadow. After forest, introduction of improved pasture in natural grassland and savanna ecosystem is another major option of carbon sequestration in soil.

Adoption of recommended soil and crop management is another option for SOC sequestration. Soil and crop management practices, which enhance biomass production, add high belowground biomass to the soil, improve soil fertility and effectively conserve soil and water also, lead to SOC sequestration. Returning crop residues, animal wastes, and other biomass to soils is important to SOC sequestration but not a practical option because of alternate uses for these by-
products as fodder, fuel, construction material and numerous other economic uses particularly in India. Adoption of appropriate farming systems and use of cover crops provide another option of C-sequestration with in terrestrial ecosystems. Mixed crop rotations and use of cover crops improve SOC contents and enhance aggregation. Diversified cropping systems with better management substantially improved SOC in semiarid-tropic soils of India (Manna et al. 2008). Adoption of conservation tillage increases C-sequestration in soil (Karlen, 1994). Lal (1989) estimated that widespread adoption of conservation tillage on soil in 400 million ha cropland by the year 2020 may lead to C-sequestration of 1481 to 4913 Tg (1 Tera gram= 10^{12} g). It is estimated that agricultural intensification in India results in C-sequestration of about 12.7 to 16.5 Tg yr^{-1}. Researchers reported that there was also a potential of sequestration of secondary carbonates; especially in irrigated soils, at about 21.8 to 25.6 Tg C yr^{-1}. The total potential of a SOC sequestration in India of 77.9 to 106.4 Tg yr^{-1} (92.2 ± 20.2 Tg yr^{-1}). Of this potential, 12.9% is through restoration of degraded soils and 45.6% through erosion prevention and management, 15.8 % through agricultural intensification and 25.7 % through secondary carbonates.

Advantages of Conventional Agricultural Practices on C-sequestration

Cropping system

In India the major cropping systems are cereal-cereal (rice-rice, cereal-cereal-cereal (rice-wheat-maize), cereal-cereal-legume (rice-wheat-greengram), legume-cereal (pluse-wheat) and oilseed-cereal (oilseed-wheat). Conventional agriculture normally reduces the SOC of the surface or plough layer. Conservation tillage systems increase SOC level. Under intensive cultivation two or three crops are grown per year and the grain yield at the rate of 10 Mg ha^{-1} yr^{-1} was achieved (Sinha and Swaminathan, 1979, Prasad, 1983). The data in Table 1 indicated that rice-wheat-green gram crop sequence has greater SOC restoration than rice-wheat followed by rice-green gram and rice-mustard possibly due to inclusion of legume in cereal-cereal cropping system.

<table>
<thead>
<tr>
<th>Cropping systems</th>
<th>Organic C (g kg^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice-wheat-fallow</td>
<td>5.8</td>
</tr>
<tr>
<td>Rice-wheat-fodder</td>
<td>6.1</td>
</tr>
<tr>
<td>Rice-wheat-green gram</td>
<td>6.8</td>
</tr>
<tr>
<td>Rice- mustard-fallow</td>
<td>5.6</td>
</tr>
<tr>
<td>Rice-mustard-fodder</td>
<td>6.0</td>
</tr>
<tr>
<td>Rice-mustard-green gram</td>
<td>6.5</td>
</tr>
<tr>
<td>Uncultivated soil</td>
<td>5.1</td>
</tr>
<tr>
<td>Initial soil status</td>
<td>5.2</td>
</tr>
<tr>
<td>L.S.D. at 5 %</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Sharma and Bali (2000)

Residue management

The usual practice of Indian farmers is to either remove the residue from field, or burning them in field and thereby SOC maintenance is difficult. Residue management as surface mulch provides a congenial environment for biodiversity, which significantly improves on SOC (Tomar et al., 1992).

Nutrient management

Among Asian countries, India has the lowest average concentration of SOC in agricultural soils (Swarup et al., 2000) especially in the Indo-Gangetic Plains. These alluvial soils are inherently fertile and high in K. However, removal of crop residue in intensive rice cropping system has contributed to the decline in SOC. This decline appears to be continuing at present in many areas, and in places where SOC is 3.0 to 4.0 g kg^{-1}, a near equilibrium at these low levels has been
reached. On the other hand, applications of manure with NPK improves the content of SOC or results in relatively higher SOC levels (Swarup et al., 2000).

**Alternate land use management**

Management practices for agro-forestry are more complex because multiple species having varied phenological, physiological and agronomic requirements are involved. The conversion of long-term arable crop land to agro-horticulture resulted in a significant increase in SOC. In this study, it was observed that the cultivation of fruit trees, coconut (Cocos nucifera L.) intercropped with guava (Psidium guajava L.) increased SOC from 3.4 to 7.8 and 2.4 to 6.2 g kg\(^{-1}\) or C-sequestered 877 kg C ha\(^{-1}\) y\(^{-1}\) and 325 kg C ha\(^{-1}\) y\(^{-1}\) after 38 and 10 years of cultivation under same agro-ecosystem. In a 20-years study, the cultivation of Prosopis juliflora, Acacia nilotica, Eucalyptus tereticornis, Terminalis arjuna and Albizia lebbek increased about 6-10 fold greater SOC as compared to control (Table 2). In this study it was observed that C-sequestration was relatively low under Eucalyptus tereticornis (168 kg C ha\(^{-1}\) y\(^{-1}\)).

Alternate land use systems, viz., agro-forestry, agro-horticulture, and agro-silviculture, are more remunerative for SOC restoration as compared to sole cropping system (Table 3). In northeast hill state India, where all the above three land use systems exists that reduce soil erosion and SOC loss considerably. In a 6 year study, organic carbon content was about double in agro-horticultural and agro-forestry systems as compared to sole cropping (Table 3). In long-term study in Indogangetic alluvial soils with rice based cropping system C-sequestration was maximum in rice-wheat-jute system (535 kg/ha/y) at Barrackpore followed by Rice-mustard-sesame (414 kg/ha/y) than rice-fallow-rice (402kg/ha/y)at CRRI, Cuttack (Table 4).

**Table 2** Long-term effect of cropping system on C-sequestration in an alkaline soil India

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil type</th>
<th>Tree species</th>
<th>Study period</th>
<th>Sampling depth(cm)</th>
<th>Initial SOC Mg/ha</th>
<th>Final SOC (Mg/ha)</th>
<th>C-sequestration(kg/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haryana, Alkaline soil</td>
<td>Acacia nilotica</td>
<td>1970-1989</td>
<td>0-120</td>
<td>4.03</td>
<td>12.3</td>
<td>413</td>
<td></td>
</tr>
<tr>
<td>CSSRI, Karnal</td>
<td>Eucalyptus tereticornis</td>
<td>1970-1989</td>
<td>0-120</td>
<td>4.03</td>
<td>7.4</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prosopis juliflora</td>
<td>1970-1989</td>
<td>0-120</td>
<td>4.03</td>
<td>13.0</td>
<td>448</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Terminalis arjuna</td>
<td>1970-1989</td>
<td>0-120</td>
<td>4.03</td>
<td>12.9</td>
<td>443</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Albizia lebbek</td>
<td>1970-1989</td>
<td>0-120</td>
<td>4.03</td>
<td>10.5</td>
<td>323</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Organic carbon in soil after six years of plantation with different land use options

<table>
<thead>
<tr>
<th>System</th>
<th>Organic C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-15 cm</td>
</tr>
<tr>
<td>Sole cropping</td>
<td>0.42</td>
</tr>
<tr>
<td>Agro- forestry</td>
<td>0.71</td>
</tr>
<tr>
<td>Agro- horticulture</td>
<td>0.73</td>
</tr>
<tr>
<td>Agro-silviculture</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 4. Long-term effect of Rice-based cropping system on C- sequestration in an Alluvial soils of India

<table>
<thead>
<tr>
<th>Location</th>
<th>Cropping system</th>
<th>Study period</th>
<th>Sampling depth(cm)</th>
<th>Initial SOC (Mg/ha)</th>
<th>Final SOC(Mg/ha)</th>
<th>C-sequestration (kg/ha/yr)</th>
<th>NPK</th>
<th>NPK+FYM/compost</th>
<th>NP</th>
<th>NPK+FYM/M/compost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gayeshpur (W.B.)</td>
<td>Rice-mustard 8-200-4-sesame 199-4</td>
<td>0-20</td>
<td>37.3</td>
<td>39.1</td>
<td>40.2</td>
<td>257</td>
<td>414</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mohanpur (W.B.)</td>
<td>Rice-wheat-6-200-4-fallow 198-4</td>
<td>0-20</td>
<td>34.0</td>
<td>35.2</td>
<td>37.2</td>
<td>63</td>
<td>168</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrackpur (W.B.)</td>
<td>Rice-wheat-1-200-4-jute 197</td>
<td>0-20</td>
<td>27.9</td>
<td>30.1</td>
<td>46.09</td>
<td>64</td>
<td>535</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CRRI,Cuttack (Orissa)</td>
<td>Rice-fallow-9-200-4-rice 196</td>
<td>0-20</td>
<td>31.6</td>
<td>39.7</td>
<td>46.1</td>
<td>225</td>
<td>402</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Mandal et al. (2006)

Soil organisms Regulate SOC turnover

The soil microorganisms are believed to play a major regulatory role in organic carbon dynamics. The abiotic factors (temperature, moisture, soil type, nature, and quantity of residues) may have a large impact on soil organic carbon dynamics by virtue of their effect on microbial activities. In sub-humid and semi-arid tropical ecosystems involving different cropping systems,
the turnover rate of SOC decreased by 3.8 fold compared to forest land (Table 5). The rate of mineralization depends on tillage, residues management, cropping practices, and erosion. Materials having wide C:N ratio are resistant to decomposition thereby restricting the supply of nitrogen for organisms and eventually resulting in increased immobilization and reduced supply of nitrogen to plant.

Table 5. Carbon pool of sub humid, semiarid tropical and arid ecosystems under different land management practices

<table>
<thead>
<tr>
<th></th>
<th>Soils organic C (g m⁻²)</th>
<th>Carbon input (g Cm⁻² yr⁻¹)</th>
<th>Turnover (yr⁻¹)</th>
<th>Soils microbial biomass C (g m⁻²)</th>
<th>C input/soil microbial biomass C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sal forestᵃ</td>
<td>Mixed forestᵇ</td>
<td>Wheat fallow</td>
<td>Mustard-sunflowerᵇ</td>
<td>Fallow land</td>
</tr>
<tr>
<td>Soils organic C (g m⁻²)</td>
<td>2854</td>
<td>2530</td>
<td>1063</td>
<td>1104</td>
<td>1144</td>
</tr>
<tr>
<td>Carbon input (g Cm⁻² yr⁻¹)</td>
<td>250</td>
<td>250</td>
<td>281</td>
<td>365</td>
<td>265</td>
</tr>
<tr>
<td>Turnover (yr⁻¹)</td>
<td>11.41</td>
<td>10.12</td>
<td>3.78</td>
<td>3.02</td>
<td>4.47</td>
</tr>
<tr>
<td>Soils microbial biomass C (g m⁻²)</td>
<td>87</td>
<td>90</td>
<td>42.30</td>
<td>31.70</td>
<td>50.8</td>
</tr>
<tr>
<td>C input/soil microbial biomass C</td>
<td>2.87</td>
<td>2.78</td>
<td>6.64</td>
<td>11.51</td>
<td>15.74</td>
</tr>
</tbody>
</table>

Source: ᵃSrivastava and Singh, 1989; ᵇChander et al., 1997; ᵇManna et al., (1996.)

**Tillage and residue management**

The SOC losses can be reduced by several tillage options such as zero tillage, reduced tillage, stubble mulching and conventional ploughing. In a 3-year field experiment, the effect of types of tillage operations and continuous addition of organic matter through use of naturally occurring wild sage (Lantana camara L.) was tested. It was observed that application of Lantana camara L. @ 10 Mg ha⁻¹ yr⁻¹ improved soil physical properties and organic carbon content. Mulch conservation tillage treatments favorably moderated the hydrothermal regimes for growing of crops. In a 45-years long-term study, use of FYM, and, organic carbon content and crop productivity in cotton sorghum system (Table 6). It was observed that seed yield of cotton failed to improve because of tap root system of cotton, which reduced for extraction of nutrients from deeper layer. In another study, residue management as surface mulch and reduced tillage provide a congenial environment for native micro flora and fauna which significantly improved SOC. In alluvial soil, application of residue mulches or compost often improves organic carbon.

**Table 6. Physico-chemical properties of the soil (0-20 cm depth) and mean yield of cotton and sorghum grown in rotation under rain fed condition for 45 years.**

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Organic Matter (%)</th>
<th>Total Nitrogen (%):</th>
<th>Available nutrients</th>
<th>Mean yield of seed cotton Mg ha⁻¹</th>
<th>Mean grain yield of sorghum Mg ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td>P</td>
<td>K</td>
</tr>
<tr>
<td>HM</td>
<td>1.16</td>
<td>0.061</td>
<td>93.8</td>
<td>13.76</td>
<td>320</td>
</tr>
<tr>
<td>PM</td>
<td>1.13</td>
<td>0.059</td>
<td>90.7</td>
<td>15.24</td>
<td>345</td>
</tr>
<tr>
<td>H</td>
<td>0.59</td>
<td>0.047</td>
<td>77.8</td>
<td>10.48</td>
<td>283</td>
</tr>
<tr>
<td>P</td>
<td>0.52</td>
<td>0.045</td>
<td>72.8</td>
<td>11.68</td>
<td>267</td>
</tr>
<tr>
<td>LSD at 5%</td>
<td>0.05</td>
<td>0.017</td>
<td>2.7</td>
<td>0.80</td>
<td>6.66</td>
</tr>
<tr>
<td>Harrowing</td>
<td>0.9</td>
<td>0.054</td>
<td>85.4</td>
<td>12.12</td>
<td>321</td>
</tr>
</tbody>
</table>
Table 3. Organic carbon in soil after six years of plantation with different land use options

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Initial SOC (g/kg)</th>
<th>SOC_e mean (SOC_e) (g/kg)</th>
<th>Steady state (SOC_e) (g/kg)</th>
<th>Loss rate (per year)</th>
<th>t_{1/2} (year)</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.6</td>
<td>4.8 ± 0.502</td>
<td>2.3 ± 1.94</td>
<td>0.098</td>
<td>7.1</td>
<td>0.5</td>
</tr>
<tr>
<td>N</td>
<td>4.6</td>
<td>4.6 ± 0.0329</td>
<td>3.54 ± 1.798</td>
<td>-0.027</td>
<td>25.7</td>
<td>0.93*</td>
</tr>
<tr>
<td>NP</td>
<td>4.6</td>
<td>4.7 ± 0.067</td>
<td>4.4 ± 0.429</td>
<td>-0.086</td>
<td>8.1</td>
<td>0.86*</td>
</tr>
</tbody>
</table>

Source: Khiani and More (1984), HM = Shallow tillage, harrowing up to 8-10 cm depth by Deccan blade harrow and manuring @ 6.2 Mg ha⁻¹ of FYM; PM = Deep tilling, ploughing up to 18-20 cm by iron plough (Kirloskar) and application of FYM at 6.2 Mg ha⁻¹; H = Shallow tillage, harrowing only up to 8-10 cm depth with Deccan blade harrow and P = Deep tillage ploughing to 18-20 cm with iron plough, NS = Not significant.
NPK
4.6  4.8 ± 0.093  4.6 ± 0.267  -0.138  5.02  0.84*

NPK+FYM  4.6  5.4 ± 0.147  5.3 ± 0.374  -0.291  2.4  0.42

* Value is significant at P<0.05, ± Indicates standard error.

Table 8. Initial status of organic C and equilibrium values for different treatments after 30 years of cultivation (Barrackpore)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Initial SOC, g kg⁻¹</th>
<th>Initial mean SOC, g kg⁻¹</th>
<th>Steady state (SOCₑ), g kg⁻¹</th>
<th>Loss rate, t¹/₂ yr⁻¹</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>7.12</td>
<td>4.9 ± 0.025</td>
<td>4.8 ± 0.018</td>
<td>-0.020</td>
<td>503</td>
</tr>
<tr>
<td>NP</td>
<td>7.12</td>
<td>4.9 ± 0.065</td>
<td>5.0 ± 0.022</td>
<td>-0.067</td>
<td>14.9</td>
</tr>
<tr>
<td>NPK</td>
<td>7.12</td>
<td>5.0 ± 0.038</td>
<td>5.1 ± 0.04</td>
<td>-0.095</td>
<td>10.7</td>
</tr>
<tr>
<td>NPK+FYM</td>
<td>7.12</td>
<td>5.4 ± 0.022</td>
<td>5.6 ± 0.017</td>
<td>-0.129</td>
<td>7.7</td>
</tr>
</tbody>
</table>

** Value is significant at P≤0.05; ± Standard error.

Cropping systems for C-sequestration in semi-arid topic (SAT) regions of India

In Vertisol, C-sequestration was maximum in cotton/ Greengram + Pigeonpea cropping system (885kg/ha/y) followed by Paddy-paddy system (861 kg/ha/y) then horticulture crop ( citrus, 745 kg/ha/y) ( Table 9). In red soil C-sequestration was maximum in intercropping system (Castor + Pigeonpea, 936kg/ha/y) than monocrop finger millet (130kg/ha/y). From different studies it was observed that to maintain SOC storage equilibrium C input in soybean–wheat system was required 888 kg C/ha/y, in rice–wheat-jute system was required 5562 KgC/ha/y in Inceptisol, 4269 kg C/ha/Yr for soybean–wheat system in Ranchi and 321 kg C /ha/y was required for soybean–wheat system in Inceptisol at Almora ( Table 10).

Table 9 - Identifying cropping systems for C-sequestration in semi-arid topic (SAT) regions of India

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil type</th>
<th>Cropping system</th>
<th>Study period</th>
<th>Sampling depth (cm)</th>
<th>Initial SOC (Mg/ha)</th>
<th>Final SOC (Mg/ha)</th>
<th>C-sequestration (kg/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madhya Pradesh</td>
<td>Typic haplusters (Kheri)</td>
<td>Paddy-wheat</td>
<td>1982-2002</td>
<td>0-30</td>
<td>19.8</td>
<td>22.5</td>
<td>135</td>
</tr>
<tr>
<td>Maharashtra</td>
<td>Typic Haplusterts (Linga)</td>
<td>Citrus</td>
<td>1982-2002</td>
<td>0-30</td>
<td>22.0</td>
<td>36.9</td>
<td>745</td>
</tr>
<tr>
<td>Maharashtra</td>
<td>Typic Haplusterts (Asra)</td>
<td>Cotton/ Greengram+Pigeonpea</td>
<td>1982-2002</td>
<td>0-30</td>
<td>17.3</td>
<td>35.0</td>
<td>885</td>
</tr>
<tr>
<td>Gujarat</td>
<td>Typic haplusterts (Semla)</td>
<td>Groundnut-wheat</td>
<td>1978-2002</td>
<td>0-30</td>
<td>27.3</td>
<td>31.9</td>
<td>209</td>
</tr>
</tbody>
</table>
Table 10 Change in SOC storage equilibrium (dCs/dt = aX-bSOC) in relation to total input require to maintain SOC in different cropping systems

<table>
<thead>
<tr>
<th>Cropping System</th>
<th>Equation</th>
<th>R²</th>
<th>Amount of C input required (kg/ha/yr) to maintained SOC</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean- wheat</td>
<td>Y=0.1806 X-160.34</td>
<td>0.95</td>
<td>888</td>
<td>Kundu et al (2001)</td>
</tr>
<tr>
<td>(IISS, Bhopal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice-wheat-jute</td>
<td>Y= 0.0536x-298.08</td>
<td>0.77</td>
<td>5562</td>
<td>Manna et al, (2005)</td>
</tr>
<tr>
<td>(Barrackpore)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean-wheat</td>
<td>Y=0.0217X-92.637</td>
<td>0.45</td>
<td>4269</td>
<td>Manna et al,(2005)</td>
</tr>
<tr>
<td>(Ranchi)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorghum-wheat</td>
<td>Y= 0.0871X-53.4</td>
<td>0.73</td>
<td>613</td>
<td>Manna et al,(2005)</td>
</tr>
<tr>
<td>(Akola)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean –wheat system</td>
<td>Y= 0.191X-61.3</td>
<td>0.98</td>
<td>321</td>
<td>Kundu et al (2007)</td>
</tr>
<tr>
<td>(Almora)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Impact of Soil Conservation and SOC Pool

Soil conservation implies reducing risks of soil erosion to the tolerable limit, which in most soils of the tropics and sub-tropics may be as low as 1 to 2 Mg ha⁻¹ yr⁻¹ (Lal, 1998). In a broader context, soil conservation may also imply improving soil quality through controlling erosion, enhancing SOC content, improving soil structure, accentuating activity of soil fauna etc. Soil conservation may be achieved through reduction of soil detachment and its transport by agents of erosion. Improving soil's resistance to forces causing detachment and transport involves enhancing soil structure. Some agricultural practices with favorable impact on soil structure include growing cover crops, sowing crops with conservation tillage, maintaining required level of soil fertility, and converting marginal and degraded lands to restorative land uses. All these practices lead to C sequestration through improvement of soil structure and enhancement of soil quality.

- Cover crops: Through formation of a quick and protective ground cover, cover crops improve SOC content, enhance soil biodiversity, improve soil structure and minimize risks of soil erosion. In addition to erosion control, several experiments around the world have also documented increase in SOC content. In Nigeria, Lal et al., 1978; 1979 observed improvements in SOC content by growing cover crops. In Ohio, Lal et al. (1998d) observed significant increases in SOC content after 5 years of growing tall fescue and smooth bromegrass.
- Conservation tillage: Beneficial impacts of conservation tillage in decreasing runoff and soil erosion are widely recognized (Lal, 1989). When used in conjunction with crop residue mulch and cover crops, conservation tillage improves soil structure and enhances SOC pool.
The benefits of conservation tillage in C sequestration are due both to increase in SOC content (Dick et al., 1998); decrease in CO₂ emissions caused by ploughing (Reicosky et al., 1998), and to reduction in fuel consumption. It is the presence of crop residue mulch on the soil surface that increases infiltration rate, decreases runoff and soil erosion, improves soil structure (Lal et al., 1980) and sequesters C in the pedosphere.

- Soil fertility management: Nutrient management is essential to increasing crop yield, improving soil quality, decreasing risks of soil erosion (through protective ground cover establishment) and improving SOC content. The long-term experiment at Rothamsted, U.K. have documented continuous increase in SOC content even after 150 years of manure application at the rate of 35 Mg ha⁻¹ yr⁻¹ (Powelson et al., 1998).

- Agricultural intensification: Adopting "good" or recommended farming practices is an important and effective strategy for soil conservation (Lal, 1989). Recommended farming practices involve agricultural intensification on prime agricultural land through use of improved varieties, adoption of appropriate cropping systems that enhance cropping intensity, and elimination of summer fallow. Soil erosion risks are extremely high on ploughed uncropped land, and accelerated soil erosion accentuates the depletion of SOC pool. Improvements in crop yield through adoption of recommended technology enhance SOC pool and improve soil quality (Manna et al, 2007).

- Conservation Reserve Program and Conservation Buffers: Conversion of marginal agricultural land, to restorative land use (e.g. natural regrowth, establishing grasses, shrubs or trees) reduces soil erosion and increases SOC pool.

References


A single gram of soil may contain many millions of individuals and several thousand species of bacteria. Soil biota also includes the roots that grow in the soil and interact with other species above and below ground. Living in the soil are plant roots, viruses, bacteria, fungi, algae, protozoa, mites, nematodes, worms, ants, maggots and other insects and insect larvae (grubs), and larger animals. Indeed, the volume of living organisms below ground is often far greater than that above ground. Together with climate, these organisms are responsible for the decay of organic matter and cycling of both macro- and micro-nutrients back into forms that plants can use. Microorganisms like fungi and bacteria use the carbon, nitrogen, and other nutrients in organic matter. Microscopic soil animals like protozoa, amoebae, nematodes, and mites feed on the organic matter, fungi, bacteria, and each other. Together, these activities stabilize soil aggregates building a better soil habitat and improving soil structure, and productivity. Here we describe the importance of soil biota towards ecosystem function and sustainability.

**Soil bacteria:** There are astonishing numbers of living organisms in most soils (as many as two billion per cubic inch). Humus-rich soils usually contain complex networks of fungal threads called hyphae. Some soil fungal hyphae form mutualistic symbioses with plant roots - the fungal threads are called mycorrhizae - and the fungi are able to gather moisture and nutrients for utilization by plants. Microorganisms are the most abundant members of the soil biota. They include species responsible for nutrient mineralization and cycling, antagonists (biological control agents against plant pests and diseases), species that produce substances capable of modifying plant growth, and species that form mutually beneficial (symbiotic) relationships with plant roots. This last group includes mycorrhizal fungi, various actinomycetes, and some bacteria. Within the soil biota, the most important groups of both destructive and resource organisms are the bacteria, fungi, nematodes, arthropods (such as mites and insects), earthworms (mostly beneficial), and weeds. Soil organisms enhance crop productivity through many processes like biological nitrogen fixation, the process by which some microorganisms fix atmospheric nitrogen and make it available to the ecosystem, offers an economically attractive and ecologically sound means of reducing external nitrogen inputs and improving the quality and quantity of internal resources. Recent estimates indicate that global terrestrial biological N$_2$ fixation ranges between 100 and 290 million tonnes of N per year, of which 40-48 million tones per year is estimated to be biologically fixed in agricultural crops and fields. Other important role is nutrient recycling, the basic nutrients required for all ecosystems, including nitrogen, phosphorus, potassium and calcium; breaking down organic matter into humus, hence enhancing soil moisture retention and reducing leaching of nutrients; and increasing soil porosity and hence water infiltration and thereby reducing surface water runoff and decreasing erosion.

**Soil Fungi:** As with the bacteria, the great diversity of fungi remains poorly documented. It has been estimated that only about 5% of fungi have so far been described. Fungi play an important a role in soil processes as do bacteria, but tend to be more abundant in slightly acid soils. They vary widely in size, preferred habitat, and mode of life. Fungal plant pathogens (e.g., some species of Fusarium and Verticillium) can cause diseases such as root rots and vascular wilts that are significant problems in many parts of the world. Many soil-borne fungal pathogens (e.g., Rhizoctonia solani and Pythium spp.) are capable of infecting a range of plant genera. Furthermore, plants infected with fungal diseases may be more vulnerable to attack by soil-dwelling insects. However, some fungi form symbiotic relationships with plant roots, enhancing the plant’s ability to take up nutrients. Many species of soil fungi are saprophytic (i.e., grow on
dead organic matter), while others are parasitic on animals or plants. Some are important antagonists or biological control agents of soil-borne pests or diseases (e.g., species of Dactyalaria and Arthrobotrys for nematodes, Beauveria and Metarhizium for insect pests, and Trichoderma and Coniothyrium for plantpathogenic fungi).

**Mycorrhizal Fungi** - A wide range of soil-borne fungi can invade the roots of higher plants to form mutually beneficial relationships called mycorrhizae. The best known of these associations are arbuscular mycorrhizae which are especially important in acid soils, where phosphorus is often the limiting nutrient. The hyphae (threads of mycelium) enhance the uptake and translocation of nutrients (particularly phosphorus) into the host plant, and the fungus in turn receives carbohydrates from the plant (Fig 3). Mycorrhizal fungi can also increase the drought tolerance of their plant partners and enhance their resistance to plant pathogens, nematodes, and toxicity caused by heavy metals. Mycorrhizal fungi can be found in the roots of grasses, some trees and shrubs, and most agricultural crops. In mature roots, the proportion of root weight attributable to a mycorrhizal fungus can vary from about 3% in sorghum to about 16% in soybean. The mycelium of a mycorrhizal fungus, which can extend several centimeters around the plant root, enhances the formation of soil aggregates, a particularly valuable trait in coarse, sandy soils. In addition, the mycelium is an important resource for fungus-grazing insects and conducts root exudates further out into the soil, enhancing the carbon supply for other members of the soil biota. Dense populations of bacteria have been found in this part of the rhizosphere, and synergistic interactions between arbuscular mycorrhizal fungi and other beneficial members of the soil microbial community (such as Trichoderma spp.) have been observed. Agricultural practices can have major impacts on mycorrhizal fungi, both positive and negative. On the one hand, conventional tillage disrupts the networks of fungal hyphae in the soil, delaying colonization of crop plants and reducing their phosphorus uptake. As a result, crop yields are lower than those obtained in zero-tillage systems. The absence of suitable host plants (over winter, for example), long-term fallowing, or continuous monoculture can all cause severe declines in soil fungal populations. On the other hand, well planned crop rotations, mixed cropping, and the use of cover crops can all conserve or enhance this important resource. Some crops are more dependent on mycorrhizal relationships than others. Faba beans and maize, for example, depend more heavily on mycorrhizae than do wheat and potatoes, while brassicas and beets do not support mycorrhizal relationships at all. Including the latter in crop rotations can therefore reduce or delay root colonization in the crops that follow.

**Microbial diversity and climate change**

The global system that regulates the earth's temperature is very complex, but many scientists believe that the increase in temperature is caused by an increase of certain gases in the atmosphere that trap energy that would otherwise escape into space. Growing awareness of global warming and ozone (O₃) depletion has led to an increased emphasis on the study of greenhouse gases viz., carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and chlorofluorocarbons (CFC). The emission of these anthropogenically mediated greenhouse gases due to an increased human activity, intensive agriculture, rapid industrialization and other associated interventions have contributed to a steady increase in global warming. It has been projected that if the present state of industrialization, dairy farming, rice cultivation, and other agriculture activities continue and/or further intensified, the atmospheric concentration of greenhouse gases will double by 2035 AD. Agriculture is considered to be one of the major anthropogenic sources of atmospheric greenhouse gases. Its important task of providing food for a steadily increasing world population is reflected in the growing damage it is causing to the environment as exemplified by the global rise in concentrations of CH₄, CO₂, and nitrogen oxides (NOx and N₂O). CH₄ and N₂O are the important greenhouse gases than other trace gases in their contribution to global warming. The
ability of CH4 and N2O molecules to absorb infrared radiation makes these gases 20–30 and 200–300, respectively, more times efficient than CO2 as a greenhouse gas, resulting in a significant contribution to the radiative forcing of the atmosphere and global climate changes. CH4, the major component of natural gas, is the second in importance as a greenhouse gas with a current ambient concentration of 1.7ppm. To many activities build up in the global atmospheric CH4 concentration is attributed. CH4 affects the earth’s atmospheric chemistry due to its multifarious role in the earth’s troposphere and stratosphere including the stratospheric ozone budget. CH4 undergoes photochemical oxidation in stratosphere and produces water vapour and results in the formation of the polar stratospheric clouds. In addition to general climatological effects, global warming may affect the global carbon cycle by greatly reducing the soil organic carbon content, which may be released as CO2 and is likely to add to the current burden of CO2 in the atmosphere. According to an estimate (World Resource Institute, Washington DC, 1990), Indian contribution to CH4 from all sources (flooded rice paddies, animal husbandary, landfills, etc) is 12% of global CH4 production. Although there are many sources of CH4 which contributes to global CH4 budget (Fig. 1) but the contribution from wetlands is substantial. Rice production is one of the most profitable ways for management of lowlands and rice serves as the most important cereal for the majority of global population, the question of reducing global rice area does not arise. On the contrary, projected increase in rice production is expected to be achieved from an intensification of rice cultivation that, in turn, may contribute to further increases in other greenhouse gases including CH4. Rice is preferentially grown under submerged conditions due to better yields than in uplands soils and positive response to modern agricultural practices. But the predominately anaerobic flooded soils promote the production of CH4, a major end product of anaerobic decomposition of organic matter (native or added).

Microbial community changes could predict whether a soil is a net sink or source of greenhouse gases, adding support to the notion that microbial populations are mediating uptake and release of gases. Studies by many researchers have found similar links and suggest that managing lands to conserve or restore specific microbial populations could mitigate greenhouse gas emissions. For that strategy to be a viable option we must first understand the mechanisms that select for microbial populations, and activity levels, leading to maximum or minimal gas emissions.

Soil harbors multiple microbial groups which regulate global greenhouse gas budget either by producing or consuming GHGs. Microbes including Methanogens, nitrifiers are known for their role in GHG production in soil or terrestrial ecosystem. Methanogens under anaerobic ecosystem produce CH4 similarly nitrifiers and denitrifiers are responsible for the atmospheric N2O. On the other hand methanotrophs consume CH4 aerobically, oxidize CH4 to CO2 as the final product. Denitrifiers under lower redox condition reduce N2O to N2. Atmospheric GHG concentration and ambient factors determine the microbial responses. For example higher CH4 atmospheric content stimulates methane consumption process by stimulating methanotrophs. Temperature, moisture content, soil factors although influence the methanotrophy like other microbes but the overall CH4 content in the environment differentiates activities of the methanotrophic microbial groups. Methanogens are stimulated in anoxic ecosystem. CH4 is produced by two groups of methanogenic microbes comprising acetoclastic and hydrogenotrophic metabolic groups. Acetoclastic generate CH4 from acetate as precursor metabolite while the later by reducing CO2 with H2. Methanogens change metabolic processes under environmental condition. Higher atmospheric CO2 concentration may stimulate hydrogenotrophic microbes than the later one. Therefore it is found that depending upon the environmental condition greenhouse gas regulating microbial metabolic processes and population changes. Considering above fact it is now challenging to manage agricultural practices for improving soil quality, increasing both
belowground (live roots) and aboveground (live cover) biomass, increasing soil organic matter, and reducing greenhouse gas emissions. To identify optimal management strategies, an understanding of microbial processes that regulate C and N cycling is essential. It is known that microbial activity is strongly influenced by both soil moisture and vegetation, and that microbial metabolism regulates the production of greenhouse gases, such as CO₂, as well as the transformation of plant material into soil organic matter.

16. Biochar for climate change mitigation

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Introduction

The application of biochar to soil is proposed as a novel approach to establish a significant, long-term, sink for atmospheric carbon dioxide in terrestrial ecosystems. There is every possibility that atmospheric CO₂ concentration will increase in near future; this further led to increased attention of scientific community to make soil a possible sink for atmospheric CO₂.

Biochar is charcoal created by pyrolysis of biomass, and differs from charcoal only in the sense that its primary use is not for fuel, but for biosequestration or atmospheric carbon capture and storage. Charcoal is a stable solid rich in carbon content, and thus, can be used to lock carbon in the soil. Biochar is of increasing interest because of concerns about climate change caused by emissions of carbon dioxide (CO₂) and other greenhouse gases (GHG). Biochar is a way for carbon to be drawn from the atmosphere and is a solution to reducing the global impact of farming (and in reducing the impact from all agricultural waste). Since biochar can sequester carbon in the soil for hundreds to thousands of years, it has received considerable interest as a potential tool to slow global warming. The burning and natural decomposition of trees and agricultural matter contributes a large amount of CO₂ released to the atmosphere. Biochar can store this carbon in the ground, potentially making a significant reduction in atmospheric GHG levels; at the same time its presence in the earth can improve water quality, increase soil fertility, raise agricultural productivity and reduce pressure on old-growth forests.

The use of biochar as soil amendments is proposed as new approach for mitigating man induced climate change along with improving soil productivity. Although, the use of biochar in agriculture is not a newer phenomenon, in primitive time farmers were using it for enhancing the production of agricultural crops. One such example is the slash and burn cultivation, which is still being practiced in some part of north-eastern India. Pre-Columbian Amazonian natives are believed to have used biochar to enhance soil productivity and made it by smoldering agricultural waste. European settlers called it Terra Preta de Indio. Following observations and experiments by a research team working in French Guiana it has been hypothesized that the Amazonian earthworm Pontoscolex corethrurus was the main agent of fine powdering and incorporation of charcoal debris to the mineral soil.

Any material to qualify for the purposes of sequestering carbon, it is necessary that it must have long residence time and should be resistant to chemical processes such as oxidation to carbon dioxide or reduction to methane. It has been suggested by many authors that the use of biochar as soil amendments meets the requirements specified above; since the biomass is protected from further oxidation from the material that would otherwise have degraded to release carbon dioxide into the atmosphere. Biochar is a high-carbon, fine-grained residue which used to be produced using centuries-old techniques by smoldering biomass (i.e., covering burning biomass with soil and letting it smolder). Biochar is another word for charcoal. The ancient method for producing charcoal for native use as fuel (and accidentally as a soil additive) was the “pit” or “trench” method, which created terra preta, or dark soil after abandonment.
Production of biochar

The yield of products from pyrolysis varies heavily with temperature. The lower the temperature, the more char is created per unit biomass. High temperature pyrolysis is also known as gasification, and produces primarily syngas from the biomass. The two main methods of pyrolysis are “fast” pyrolysis and “slow” pyrolysis. Fast pyrolysis yields 60% bio-oil, 20% biochar, and 20% syngas, and can be done in seconds, whereas slow pyrolysis can be optimized to produce substantially more char (~50%), but takes on the order of hours to complete. For typical inputs, the energy required to run a “fast” pyrolyzer is approximately 15% of the energy that it outputs. Modern pyrolysis plants can be run entirely off of the syngas created by the pyrolysis process and thus output 3–9 times the amount of energy required to run. Alternatively, microwave technology has recently been used to efficiently convert organic matter to biochar on an industrial scale, producing ~50% char.

The ancient method for producing biochar as a soil additive was the “pit” or “trench” method, which created terra preta, or dark soil. While this method is still a potential to produce biochar in rural areas, it does not allow the harvest of either the bio-oil or syngas, and releases a large amount of CO₂, black carbon, and other GHGs (and potentially, toxins) into the air. Modern companies are producing commercial-scale systems to process agricultural waste, paper byproducts, and even municipal waste.

There are three primary methods for deploying a pyrolysis system. The first is a centralized system where all biomass in the region would be brought to a pyrolysis plant for processing. A second system would effectively mean a lower-tech pyrolysis kiln for each farmer or small group of farmers. A third system is a mobile system where a truck equipped with a pyrolyzer would be driven around to pyrolyze biomass. It would be powered using the syngas stream, return the biochar to the earth, and transport the bio-oil to a refinery or storage site. Whether a centralized system, a distributed system, or a mobile system is preferred is heavily dependent on the specific region. The cost of transportation of the liquid and solid byproducts, the amount of material to be processed in a region, and the ability to feed directly into the power grid are all factors to be considered when deciding on a specific implementation.

Unless crops are going to be dedicated to biochar production, the residue-to-product ratio (RPR) for the feedstock material is a useful gauge of the approximate amount of feedstock that can be obtained for pyrolysis after the primary product is harvested and the waste remains. The amount of crop residue available to be used for pyrolysis can be determined by using the RPR, and the collection factor (the percent of the residue not used for other things). For instance, Brazil harvests approximately 460 Mt of sugarcane annually, with an RPR of 0.30, and a collection factor (CF) of 0.70 for the sugar cane tops, which are normally burned on the field. This translates into approximately 100 Mt of residue which can be pyrolyzed to create energy and soil additives.
annually. Adding in the bagasse (sugarcane waste) (RPR=0.29 CF=1.0) which is currently burned inefficiently in boilers, raises the total to 230 Mt of pyrolysis feedstock just from sugarcane residues. Some plant residue, however, must remain on the soil to avoid heavily increased costs and emissions from nitrogen fertilizers.

**Carbon sink potential**

The stability of biomass-derived black carbon (BC) or biochar as a slow cycling pool in the global C cycle is an important property and is likely governed by environmental condition. Because of its macromolecular structure dominated by aromatic C, biochar is more recalcitrant to microbial decomposition than uncharred organic matter. Direct estimations of BC decomposition rates are absent because the BC content changes are too small for any relevant experimental period. About 0.5% BC was decomposed per year under the optimal conditions. If BC decomposes 10 times slower under natural conditions, the mean residence time (MRT) of BC was about 2000 years, and the half-life was about 1400 years.

Biochar can sequester carbon in the soil for hundreds to thousands of years, like coal. Modern biochar is being developed using pyrolysis to heat biomass in the absence of oxygen in kilns. However, to the difference of coal and/or petroleum charcoal, when incorporated to the soil in stable organo-mineral aggregates does not freely accumulate in an oxygen-free and abiotic environment. This allows it to be slowly oxygenated and transformed in physically stable but chemically reactive humus, thereby acquiring interesting chemical properties such as cation exchange capacity and buffering of soil acidification. Both are precious in nutrient- and clay-poor tropical soils. Modern biochar production can be combined with biofuel production in a process that may produce 3 to 9 times more energy than invested, is carbon-negative (withdraws more carbon from the atmosphere than it releases) and rebuilds geological carbon sinks.

Biochar is a high-carbon, fine-grained residue which today is produced through modern pyrolysis processes. Pyrolysis is the direct thermal decomposition of biomass in the absence of oxygen to obtain an array of solid (biochar), liquid (bio-oil) and gas (syngas) products. The specific yield from the pyrolysis is dependent on process conditions, and can be optimized to produce either energy or biochar. Even when optimized to produce char rather than energy, the energy produced per unit energy input is higher than for corn ethanol.

**Biochar for mitigation of climate change-potential and feasibility**

Biochar can be used to hypothetically sequester carbon on centurial or even millennial time scales. In the natural carbon cycle, plant matter decomposes rapidly after the plant dies, which emits CO$_2$; the overall natural cycle is carbon neutral. Instead of allowing the plant matter to decompose, pyrolysis can be used to sequester some of the carbon in a much more stable form. Biochar thus removes circulating CO$_2$ from the atmosphere and stores it in virtually permanent soil carbon pools, making it a carbon-negative process. In places like the Rocky Mountains, where beetles have been killing off vast swathes of pine trees, the utilization of pyrolysis to char the trees instead of letting them decompose into the atmosphere would offset substantial amounts of CO$_2$ emissions. Although some organic matter is necessary for agricultural soil to maintain its productivity, much of the agricultural waste can be turned directly into biochar, bio-oil, and syngas. The use of pyrolysis also provides an opportunity for the processing of municipal waste into useful clean energy rather than increased problems with land space for storage.

Biochar is believed to have long mean residence times in the soil. While the methods by which biochar mineralizes (turns into CO$_2$) are not completely known, evidence from soil samples in the Amazon shows large concentrations of black carbon (biochar) remaining after they were abandoned thousands of years ago. The amount of time the biochar will remain in the soil depends on the feedstock material, how charred the material is, the surface: volume ratio of the particles, and the conditions of the soil the biochar is placed in. Estimates for the residence time range from
100 to 10,000 yrs, with 5,000 being a common estimate. Lab experiments confirm a decrease in carbon mineralization with increasing temperature, so carefully controlled charring of plant matter can increase the soil residence time of the biochar C.

Under some circumstances, the addition of biochar to the soil has been found to accelerate the mineralization of the existing soil organic matter, probably from the excessive potash and increased pH from biochar but this would only reduce and not suppress the net benefit gained by sequestering carbon in the soil by this method. Furthermore, the suggested soil conditions for the integration of biochar are in heavily degraded tropical soils used for agriculture, not organic matter-rich boreal forest soils (as tested in the above reference).

Assuming biochar is effective at storing carbon for adequately long periods of time, serious questions remain as to whether biochar will play a significant role in combatting global warming. First is a question of scale. Assuming a natural carbon cycle in which trees absorb and release 120 billion tonnes of carbon per year, and human-caused emissions of 8 billion to 10 billion tonnes per year, in order to address even half of human-caused emissions, biochar would require harvesting of 3% to 4% of the world's forests per year - an enormous undertaking.

There is another combined question of policy and markets. Energy produced from producing biochar is less than that produced from burning biomass. Thus, in order to scale up biochar to industrial levels worldwide, there would need to be a significant price imposed on carbon emissions so as to make biochar more financially attractive than burning. Yet if there were a significant price on carbon emissions, alternative (non-biochar) techniques for carbon reduction would become increasingly cost-effective.

Johannes Lehmann, of Cornell University, estimates that pyrolysis can be cost-effective for a combination of sequestration and energy production when the cost of a CO₂ ton reaches $37. As of mid-February 2010, CO₂ is trading at $16.82 ton on the European Climate Exchange (ECX), so using pyrolysis for bioenergy production may be feasible even if it is more expensive than fossil fuels.

The technology for biochar sequestration does not require a fundamental scientific advance. The underlying production technology is robust and simple, making it appropriate for many regions of the world.

Positive and negative effects on soil

Biochar may be a substance mostly suited to severely weathered and deprived soils (low pH, low potassium, low or no humus). Clearly, there is the real potential for carbon sequestration, simply because biochar is so stable and is not accessible to normal microbial decay. Soils require active carbon to maintain micro and macro populations, not the inactive form found in biochar. Biochar can prevent the leaching of nutrients out of the soil, partly because it absorbs and immobilizes certain amounts of nutrients, however, too much immobilization can be harmful. It has been reported to increase the available nutrients for plant growth, but also depress them increase water retention, and reduce the amount of fertilizer required. Additionally, it has been shown to decrease N₂O (Nitrous oxide) and CH₄ (methane) emissions from soil, thus further reducing GHG emissions. Although it is far from a perfect solution in all economies, biochar can be utilized in many applications as a replacement for or co-terminous strategy with other bioenergy production strategies.

Biochar implications in agriculture

Response of crops to biochar application rate is essential for devising suitable strategy for long term carbon sequestration goal. Biochar fertilizer is another product being considered of relevance to C sequestration. It is reported that black C can produce significant benefits when applied to agricultural soils in combination with some fertilizers. Apart from positive effects in both reducing emissions and increasing the sequestration of greenhouse gases, the production of
biochar and its application to soil will deliver immediate benefits through improved soil fertility and increased crop production.

Biochar can be used as a soil amendment to affect plant growth yield, but only for plants that love high potash and elevated pH, improve water quality, reduce soil emissions of GHGs, reduce leaching of nutrients, reduce soil acidity, and reduce irrigation and fertilizer requirements. It is reported that black C can produce significant benefits when applied to agricultural soils in combination with some fertilizers. Increase in crop yield to the tune of 45-250% has been reported by application of biochar along with chemical fertilizers. Soil water retention properties, saturated hydraulic conductivity and nutrients availability increased with the application of biochar. Biochar application reduced CO\textsubscript{2} respiration, nitrous oxide (N\textsubscript{2}O) and methane (CH\textsubscript{4}) production, and decreased dissipation rate of herbicide in soil.

These positive qualities are dependent on the properties of the biochar, and may depend on regional conditions including soil type, condition (depleted or healthy), temperature, and humidity. Modest additions of biochar to soil were found to reduce N\textsubscript{2}O emissions by up to 80% and completely suppress methane emissions.

Pollutants such as metals and pesticides seep into the Earth's soil and contaminate the food supply. This pollution reduces the amount of land suitable for agricultural production and contributes to global food shortages. Studies have reported positive effects to crop production in highly degraded and nutrient poor soils. Biochars can be designed to have specific qualities that can target distinct properties of soils. Application of biochar reduces leaching of critical nutrients, creates a higher crop uptake of nutrients, while also providing greater soil availability of nutrients. Biochar added at 10% levels reduced contaminant levels in plants by up to 80%, while reducing total chlordane and DDX content in the plants by 68 and 79%, respectively.

Switching from slash and burn to slash and char techniques in Brazil can both decrease deforestation of the Amazon and increase the crop yield. Under the current method of slash and burn, only 3% of the carbon from the organic material is left in the soil. Switching to slash and char can sequester up to 50% of the carbon in a highly stable form. Adding the biochar back into the soil rather than removing it all for energy production is necessary to avoid heavy increases in the cost and emissions from more required nitrogen fertilizers. Additionally, by improving the soil tilth, fertility, and productivity, the biochar enhanced soils can sustain agricultural production, whereas non-amended soils quickly become depleted of nutrients, and the fields are abandoned, leading to a continuous slash and burn cycle and the continued loss of tropical rainforest. Using pyrolysis to produce bio-energy also has the added benefit of not requiring infrastructure changes the way processing biomass for cellulosic ethanol does. Additionally, the biochar produced can be applied by the currently used tillage machinery or equipment used to apply fertilizer.

**Energy production: bio-oil**

Bio-oil can be used as a replacement for numerous applications where fuel oil is used, including fueling space heaters, furnaces, and boilers. Additionally, these biofuels can be used to fuel some combustion turbines and reciprocating engines, and as a source to create several chemicals. If bio-oil is used without modification, care must be taken to prevent emissions of black carbon and other particulates. Syngas and bio-oil can also be “upgraded” to transportation fuels like biodiesel and gasoline substitutes. If biochar is used for the production of energy rather than as a soil amendment, it can be directly substituted for any application that uses coal. pyrolysis also may be the most cost-effective way of producing electrical energy from biomaterial. Syngas can be burned directly, used as a fuel for gas engines and gas turbines, converted to clean diesel fuel through the Fischer–Tropsch process or potentially used in the production of methanol and hydrogen.
Bio-oil has a much higher energy density than the raw biomass material. Mobile pyrolysis units can be used to lower the costs of transportation of the biomass itself if the biochar is returned to the soil and the syngas stream is used to power the process. Bio-oil contains organic acids which are corrosive to steel containers, has a high water vapor content which is detrimental to ignition, and, unless carefully cleaned, contains some biochar particles which can block injectors. The greatest potential for bio-oil seems to be its use in a bio-refinery, where compounds that are valuable chemicals, pesticides, pharmaceuticals or food additives are first extracted, and the remainder is either upgraded to fuel or reformed to syngas.

**Future research interventions**

Although, biochar as soil amendments for improving soil quality and soil carbon sequestration has attracted wide scale global attention, there is inadequate knowledge on the long term application of soil amendment properties of these materials produced from different feed stocks and under different pyrolysis conditions. The fundamental mechanisms by which biochar could provide beneficial function to soil and the wider function of the agro-ecosystem are poorly described in terms of providing the predictive capacity that is required. Although there are contradictory reports of beneficial use of biochar in agriculture but it seems biochar could be the panacea for mitigating the increasing carbon dioxide concentration in environment provided its rate of application and mechanism of action is fully understood. There is a need to monitor the changes in physical, chemical, hydrological and ecological settings of soil under the long term application of biochar. Also it must be ascertained the response of different crops to biochar application under the different agro-ecological regions.

**Further reading**

Introduction

Production, formulation, storage, distribution of these inputs and application with tractorized equipment lead to combustion of fossil fuel, and use of energy from alternate sources, which also emits CO2 and other greenhouse gases (GHGs) into the atmosphere. Thus, an understanding of the emissions expressed in kilograms of carbon equivalent (kg CE) for different tillage operations, fertilizers and pesticides use, supplemental irrigation practices, harvesting and residue management is essential to identifying C-efficient alternatives such as biobuls and renewable energy sources for seedbed preparation, soil fertility management, pest control and other farm operations. Land use and land cover change and agricultural practices contribute about 20% of the global annual emission of carbon dioxide (CO2) (IPCC, 2001). A significant part of the emission due to agricultural practices can be reduced by the worldwide adoption of RMPs. Regarding to C emissions; agricultural practices may be grouped into primary, secondary and tertiary sources (Gifford, 1984). Primary sources of C emissions are either due to mobile operations (e.g., tillage, sowing, harvesting and transport) or stationary operations (e.g., pumping water, grain drying). Secondary sources of C emission comprise manufacturing, packaging and storing fertilizers and pesticides. Tertiary sources of C emission include acquisition of raw materials and fabrication of equipment and farm buildings, etc. Therefore, reducing emissions implies enhancing use efficiency of all these inputs by decreasing losses, and using other C-efficient alternatives.

Farmers all over the world have plowed the land in preparation for planting a crop. When land is plowed, the soil is inverted (turned over) so all of the old crop residue and other plant material is buried. The farmer then has bare soil, which is loose on the top (Esdail 2009). Conventional tillage and erosion deplete SOC pools in agricultural soils. Thus, soils can store C upon conversion from plow till to no till or conservation tillage, by reducing soil disturbance, decreasing the fallow period and incorporation of cover crops in the rotation cycle. Eliminating summer fallowing in arid and semi-arid regions and adopting no till with residue mulching improves soil structure, lowers bulk density and increases infiltration capacity (Shaver et al., 2002). However, the benefits of no till on SOC sequestration may be soil/site specific, and the improvement in SOC may be inconsistent in fine textured and poorly drained soils (Wander et al., 1998). Some studies have also shown more N2O emissions in no till (Mackenzie et al., 1998). Similar to the merits of conservation tillage reported in North America, Brazil and Argentina (Lal, 2000; Sa et al., 2001) several studies have reported the high potential of SOC sequestration in European soils (Smith et al., 1998, 2000a,b). Keeping above facts in view a comparative study of CA and Conventional practices was conducted in 4 states (Punjab, Haryana, Up and MP) of India. The purpose of study was to calculate difference of carbon emission in CA and conventional practices.

With the introduction mechanized CA practices, farmers are able to finalize planting earlier, and can even free the equipment for service hire to neighbors. These CA equipment can reduce the delays in planting and also benefit neighbors who can hire this equipment and be able to plant within the first planting window, commonly associated with better yield gains. Smallholder farmers can also form groups to mobilize resources for equipment purchase to overcome the equipment cost problem. Local production of CA equipment for the smallholder agricultural sector has been almost non-existent prior to 2005. Appropriate mechanized CA equipment is still not widely available in local markets, so an extensive participatory process is required to test
mechanized CA technologies and demonstrate the improved performance compared with conventional tillage practice. More than one season of on-farm testing is also needed to perfect this equipment. Farmers purchasing mechanized CA equipment need extensive training on calibration, operation and maintenance of the new implements, and the CA system. The development and promotion of mechanized CA will assist in creating a demand for these equipment, which in turn will help manufacturers continue to produce the equipment. Farmer demand should take over after some time, and make the agriculture sustainable. Equipment manufacturers also need pre-financing to allow an initial investment in the production of mechanized CA equipment, and support production of sufficient quantities to meet the growing demand.

A pilot survey, for assessing the present status of CA machinery and their use in carbon use pattern, was conducted in four selected northern states (Punjab, Haryana, MP and UP) of India. Total 207 farmers were taken for the studied that were practicing both conservation and conventional agricultural practices. Total input and output data for rice-wheat cropping system were recorded and converted them in farm of carbon emission presented in Table 1.

Table 1: Carbon emission coefficients for different Agricultural inputs

<table>
<thead>
<tr>
<th>S. N.</th>
<th>Fuel/chemical sources</th>
<th>Equivalent carbon emission kg CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>One lit of fuel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>2.6</td>
</tr>
<tr>
<td>(B)</td>
<td>One kg of Fertilizers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nitrogen</td>
<td>0.9-1.8</td>
</tr>
<tr>
<td></td>
<td>Phosphorus</td>
<td>0.1-0.3</td>
</tr>
<tr>
<td></td>
<td>Potassium</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td></td>
<td>Lime</td>
<td>0.03-0.23</td>
</tr>
<tr>
<td>(C)</td>
<td>One kg a.i. of Chemicals</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Herbicides</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2, 4-D</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>Atrazine</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Glyfosate</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>Paraoquat</td>
<td>9.2</td>
</tr>
<tr>
<td>12.</td>
<td>Insecticide</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parathion</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Phorate</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Lindane</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Malathian</td>
<td>4.6</td>
</tr>
<tr>
<td>13.</td>
<td>Fungicide</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ferbam</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Maneb</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Captan</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Benomyl</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Source: (Lal, 2004)

The documentation on use of CA machineries was also done based on survey of 207 farmers from four states of northern India. State wise commonly used CA machineries are given in Table 2.

Table 2: List of CA machineries being used in surveyed four states

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Name of Machine</th>
<th>Being used in states</th>
<th>Custom hiring rate</th>
<th>Fuel consumption, l/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Zero-till drill</td>
<td>Punjab, Haryana, UP and MP</td>
<td>₹ 200 /h</td>
<td>3.5</td>
</tr>
<tr>
<td>2.</td>
<td>Turbo happy seeder</td>
<td>Punjab and Haryana</td>
<td>₹ 300 /h</td>
<td>3-4</td>
</tr>
</tbody>
</table>
### Brief description about CA machinery and their source of availability:

#### Laser Land Leveller
Unevenness of the soil surface has a significant impact on the germination, stand and yield of crops. Laser Land Leveller is used to level the field within certain degree of slope using a guided laser beam throughout the field. As the traditional methods of levelling land are cumbersome, time consuming as well as expensive farmers also recognize this equipment. Machine control system to be mounted on tractor consisting of:
- Light Sensor (Receiver) with Carry Case to be mounted on a mast directly above bucket
- Light Auto Panel with keys and LED display for manual and automatic control of hydraulics of tractor
- Power cable for powering system from tractor power 112V / 24V
- Cable connecting 5 light sensor to Auto Panel
- Cable connecting Auto panel to Valves of tractor for

<table>
<thead>
<tr>
<th>Name &amp; Address</th>
<th>Contact No., Fax and Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>BeriUdyog P (Ltd.) 100-101/3, HSIDC, Karnal</td>
<td>Ph: 0184-2221571-72, 73, 74, 2262659, 2270415</td>
</tr>
<tr>
<td>OsawUdhyog, Vill: Mangli, P.O., KhuddaKalan, Ambala-133004</td>
<td>Ph: 0171-2891609, 2005234</td>
</tr>
</tbody>
</table>

#### Direct rice seeder
Punjab and Haryana

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#### Rototil drill
Punjab and UP

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<th>Name &amp; Address</th>
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</thead>
<tbody>
<tr>
<td>Happy seeder</td>
<td>Development of the Happy Seeder (HS) machine was initiated at Punjab Agricultural University, Ludhiana in collaboration with Australian scientists and funded by the Australian Centre for international Agricultural Research (ACIAR) in 2002. There are three major prototypes developed till date, each being an improvement on the previous versions and having their own particular advantages. The first two versions helped cut and lift the standing stubble and loose straw ahead of the sowing tynes so that they could engage in bare soil, and then deposit the stubble as mulch on the sown area behind the seed drill. The third version of the Happy Seeder consists of a rotor for managing the paddy residues and a zero till drill for sowing wheat. Flails are mounted on the straw management rotor that cuts (hits/shear) the standing stubbles/loose straw encountered</td>
</tr>
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</tbody>
</table>

#### Few Manufacturers of Laser Land Leveller

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</table>
in front of the sowing tyne and cleans each tyne twice in one rotation of rotor for proper placement of seed in soil. The rotor blades/flails guide the residue as surface mulch between seeded rows.

Instead, the straw is chopped finely with the inclusion of fixed blades on the inside of the rotor volute and concave rotor blades in front of the improved design inverted-T sowing tynes. All the furrow openers (tynes) are now on the same bar and are curved so that there is only a very small clearance (15 mm) between the rotating flails and tynes, which are swept clean twice with every revolution of the rotor and the straw is fed between the tynes. As a result, the sowing lines are now more exposed, and visible. The rotor speed is only marginally higher than in Combo Happy Seeder (1300-1500 rpm). Moreover, the Turbo Seeder does not have a strip-till mechanism and the tynes are on a single toolbar.

Few Manufacturers of Happy Seeder

| Dashmesh Mechanical Works, Nabha-Malerkota Road, Amargarh, Distt. Sangrur-148022 | Ph: 01675-284221 Mob: 98151-74313 Fax:01675-285999 Email: info@dashmesh.net |
| KambojKrishUdhyog, Kaithal Road, Pehowa | Mob: 9915445406, 09876320842 |

Tractor mounted Till Planter

After combine harvesting of paddy, the farmers face a lot of problems in timely sowing of wheat. Heavier soils normally require 8-12 operations with conventional equipment for proper seedbed preparation. Consequently the sowing of wheat is either delayed or done in poorly prepared seed-bed with reduction in the yield. This machine has proved very useful for farmers for timely sowing of wheat after combine harvesting paddy in sandy loam as well as silt clay loam soil. The number of field operations has been reduced and the yield of wheat crop was also at par with that from conventional tillage and sowing practices.

In heavier soils, where conventional equipment require 6-8 operations for soil penetration the till planter offers 30-40% savings in time (more than 10 ha/h), labour and cost of operation (15-20%). Details of field performance results are given in the Table below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of sowing, mm</td>
<td>50-72</td>
</tr>
<tr>
<td>Speed of operation, km/h</td>
<td>2.50-3.50</td>
</tr>
<tr>
<td>Field capacity, ha/h</td>
<td>0.18-0.25</td>
</tr>
<tr>
<td>Fuel consumption, l/h</td>
<td>4-4.5</td>
</tr>
<tr>
<td>Germination count/m length, (30 DAS)</td>
<td>34-39</td>
</tr>
<tr>
<td>Yield, kg/ha</td>
<td>4185-4730</td>
</tr>
</tbody>
</table>

In sandy loam soil condition, collection and entanglement of straw near the tines of sowing this caused non-uniform dropping of seeds in the furrow. The tractor mounted till planter performed better in silt clay loam soil where one pass of tractor mounted disc harrow was added.

Controlled traffic slit drill

The controlled traffic slit drill was designed for zero till seeding in straw fields after grain combining. The machine was operated on fixed path for seeding on the area within the rear wheels of the tractor. The machine consisted of 07 no. of rotary slit cutter(Primary openers) units mounted on a common shaft for cutting the surface straw/stubbles and opening narrow and shallow slits (With = 10 mm and depth
=100 mm) in soil followed by drill tines with secondary furrow openers for placing seed and fertilizer into the slit.

**Tractor drawn plastic mulch laying machine**

Plastic mulch laying machine is used for lying of plastic film (width of film=500 mm-1500mm) for mulching for efficient moisture conservation, raising soil temperature conducive for germination of seeds in colder weather, weed control and maintenance of soil structure and environment. Machine consists of two concave discs of 400 mm diameter, two pneumatic press wheels of 350 mm diameter, two pneumatic transport wheels of 600 mm and two scrapers for covering plastic film roll edges with soil are mounted on telescopically adjustable shanks with the help of clamps on the main frame. Mountings of press wheels are assisted with compression springs. Roll holder are mounting of plastic sheet roll on roll holder assembly with adjustments for height and width.

**Pneumatic Seed Metering Device for Planting Cottonseeds**

A modular pneumatic seed-metering system having a disc of 244.5mm outside diameter and 7mm thickness with equidistant holes at a distance of 231mm pitch circle diameter was used. Seed spacing was regulated by changing the rotational speed or by changing the number of holes/cells on the metering disc. The disc was mounted to a vacuum retaining plate made of Bakelite material having 275mm outside diameter and 40 mm thickness. A drive wheel was connected to the pneumatic seed-metering system through chain and sprockets to provide rotation to the seed disc. Suction pressure inside the metering unit was created by connecting it to a vacuum pump.

**Straw Reaper with in-built trailer**

Combine harvesting is widely practised by medium and large farmers for wheat harvesting on custom hire basis due to scarcity of labour during harvesting period. Straw reaper was developed to retrieve bhusa left over as a result of combining which was otherwise being burnt by the farmers to have clear field for the next cropping season. The machine required operation of a tractor trailer along with the unit for collection of the harvested straw by the machine. The system also was adopted by the farmers on custom hire basis. The system was promoted under custom hiring by the institute since March, 2007. Details of villages and farmers benefited as a result of the program are given at annexure-1. It was quite possible with the farmers as it resulted in retrieval of the wheat straw, which is an important animal feed and has economic value (Rs.400 – 500/q).

**RAISED BED PLANTER**

Bed planting system is referred to the planting and cultivation of crops on raised beds. Generally wheat and some other crops are sown on raised beds. Researchers from several organizations (DWR, Karnal; PAU, Ludhiana; CIAE, Bhopal; PDCSR, Modipuram; CCS, HAU,Hisar; RWC-IGP and CIMMYT etc.) have reported that planting wheat on raised beds has improved yield,
increased fertilizer use efficiency, reduced herbicides dependence. Facilitated better weed management and mobility in the crops field for other intercultural operations, less lodging of crops and reduced seed rate. It also helps in better fertilizer and irrigation use efficiency. The total cost of production of raised bed in comparison to flat beds is found to be reduced marginally in the fresh beds but when beds are reused the reduction is about 25-35%. Bed planting system is gaining importance among farmers in different part of the country due to more benefit-cost ratio as compared to flat bed.

**TRACTOR MOUNTED ZERO-TILL SEED-CUM-FERTILIZER DRILL**

Zero-till drilling of wheat is becoming the most successful resource-conserving technology and an attractive alternative to the conventional tillage in sowing of wheat after rice. In Indo-Gangetic plains of Punjab, Haryana, Uttar Pradesh, and Bihar and in the irrigated zones of Madhya Pradesh and Rajasthan, farmers are shifting to direct drilling of wheat after the harvest of rice to maintain the timeliness in delayed wheat sowing conditions. Direct zero-till drilling offers the apparent advantage of timely planting at reduced time, fuel, labour and drastic reduction in tillage intensity, resulting in significant cost savings as well as potential gains in yield through earlier planting of wheat. Thus, reducing the drudgery involved in the task and reducing the cost of production. Moreover zero-till drilling carries special significance and has proved more cost effective in situations where late harvesting of rice compels delay in sowing of wheat.

### Few Manufacturers of Zero Till seed-cum-ferti drill

<table>
<thead>
<tr>
<th>Name &amp; Address</th>
<th>Contact No., Fax and Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dharti Agro Engineering (Shaper) Survey No-35, Plot No-6, Gondal Road, Rajkot-2 (Gujrat)</td>
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<td></td>
<td>Mob: 9426206420</td>
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<td>Aggarwal Agriculture Works, Jind Road, Assandh (Karnal)</td>
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<td>Azad Engineering Works, Jhansa Road Thanesar, Kurukshetra</td>
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<td></td>
<td>Mob: 9896134487</td>
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<td>BeriUdyog P (Ltd.) 100-101/3, HSIDC, Karnal</td>
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<td>Ph: 01744-235432,</td>
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<td></td>
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</tr>
<tr>
<td>Punjab Agro Industries, Near NamasteyChowk, Sham Nagar, G.T. Road, Karnal</td>
<td>Ph: 0184-2261055, 3100283</td>
</tr>
<tr>
<td>Jajiv Farm Machinery, 158, Automobile Market, Hisar- 125001</td>
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<td>Bismillah Engineering Works</td>
<td>Ph: 01662-245008</td>
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<tr>
<td>Ambigeri Crass, Annigeri-582 201, Tal. Navalguod, Dist. Dharwad</td>
<td>Mob: 9416136498, 94166165992</td>
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<tr>
<td>Canara Agro Industries, Boloor, Mangalore-575003</td>
<td>Ph: 0836-2371980</td>
</tr>
<tr>
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<td>Telefax: 08482-225414, Mob: 9886676116</td>
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<tr>
<td></td>
<td>Email: <a href="mailto:p_s_gagi@yahoo.com">p_s_gagi@yahoo.com</a></td>
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Seed drill for sowing on furrow slants

The concept of sowing of crops on the slant surfaces of a specifically created furrow was devised. The furrow facilitated the collection of runoff water to create and maintain a high moisture concentration in the plant root zone, resulting in 26% increases in plant height and 30–70% increase in grain yield compared to the conventional method. A three-furrow (six-row), multi-crop seed cum fertiliser drill was designed and developed with the provision for a seed-pressing device. Performance of the seed drill was evaluated and compared to a conventional seeding system with pearl millet (Variety: HHB-67), green gram (Variety: RMG-62), moth bean (Variety: RMO-40) and cluster bean (Variety: RGC-936) crops. About 30–40% more grain yield was obtained for crops sown using the above-mentioned seed drill compared to the conventional method of sowing in year with normal rainfall (389.3mm/ year⁻¹). Greater increases in grain yield (60–70%) were recorded under severe moisture stress conditions (wilting stage) arising from a dry spell (28 days) towards the end of the monsoon season encountered during Kharif, 2001–2002.

Subsoiler-cum-Differential Rate Fertilizer Applicator
A subsoiler-cum-differential rate fertilizer applicator was designed and developed by selecting the best parameters from previous studies. The equipment consisted of a rectangular frame, a main winged tine, two shallow leading winged tines, a depth control device, a fertilizer box of 100 kg capacity, positive feed type fertilizer metering devices and a ground wheel with chain and sprockets for transmitting power to the metering mechanism. The equipment had the option to place fertilizers up to a 500-mm soil depth by the main winged tine and delivering fertilizer up to 250-mm deep using the leading tines, thereby helping to place fertilizer at different depths in vertical soil profile in a single pass. All three tines had independent metering systems. Options were provided to meter and deliver either 33.3% or 25.0% or 20.0% of the total recommended fertilizers with the main tine and the remaining amount through two shallow leading tines. The laboratory evaluations indicated a coefficient of uniformity of more than 90% for application rates of 250, 500, 750 and 1000 kg/ha. The equipment was tested in the field to observe its performance on sugarcane with results showing an increase of 16.2%, 16.4% and 35.4% in yield as compared to conventional ploughing with in-furrow fertilizer application (Control). Subsoiling alone increased the cane weight, number of millable cane and cane yield by 4.3%, 11.4% and 15.9% compared to the control.

Till Plant Machine

A tractor drawn (TD) till plant machine was designed and developed with the help of computer aided design package for adoption of minimum till technology by the farmers, in black cotton soil conditions. This machine was evaluated and compared with the performance of a zero till drill and conventional practices at Jawaharlal Nehru Agricultural University farms as well as at a farmer’s fields. It was found that the total time and cost required for tillage and sowing operations by till plant machine was 5.09 h/ha and Rs. 410.37/ha, which is 72.23 per cent less time required than conventional practices of wheat cultivation but is 28.83 per cent more time required than zero till drill practices. The average yield by tractor till plant machine was 26.96 q/ha, whereas, by conventional practices and tractor drawn zero till drill was 25.91 and 22.72 q/ha, respectively. The soil conditions were also found better in the case of the T.D. till plant machine.

Comparison of carbon emission in field preparation among four surveyed states

Traditional field preparation and sowing practices (for major cropping system of the state) observed to emit more carbon as compared to CA practices in all four surveyed states. Maximum carbon emission in conventional field preparation was observed in UP state (288 kg CE/ha) followed by Haryana (287 kg CE/ha), Punjab (269 kg CE/ha) and MP (127 kg CE/ha). However, in CA sowing practices maximum emission was observed in Haryana (163 kg CE/ha) followed by UP (151 kg CE/ha), Punjab (81 kg CE/ha) and MP (68 kg CE/ha). Carbon emission per unit grain production, for both conventional and CA practices, was found maximum in UP (70 and 40 kg CE/t) followed by Haryana (30 and 20 kg CE/t), Punjab (24 and 09 kg CE/t) and MP (20 and 10 kg CE/t).

Comparison of carbon emission in by applied chemical in major cropping system in surveyed states
Carbon emission from applied chemicals (DAP, urea, insecticide and weedicide) in conventional sowing practice was maximum in Punjab (463 kg CE/ha) followed by Haryana (154 kg CE/ha), UP (254 kg CE/ha) and MP (321 kg CE/ha). Similar pattern was observed in CA practices also. However, maximum carbon emission per ton grain production in both conventional and AC practices was found in UP (60, 60 kg CE/t) followed by MP (49, 50 kg CE/t), Punjab (40, 40 kg CE/t) and Haryana (15, 10 kg CE/t).

**Total annual carbon mission in major cropping system of the state**

Total annual carbon emission in both conventionally and CA sown practices in rice-wheat cropping system were almost same and found maximum in Punjab (731 kg CE/ha) followed by Haryana (542 kg CE/ha), UP (448 kg CE/ha) and MP (441 kg CE/ha). However, carbon emission per ton grain production, in both CP and CA practices, was found maximum in UP followed by MP, Punjab and Haryana states.

**Percentage saving in CA practices as compared to conventional practices**

The projected reduction in carbon emission with the application of CA practice was maximum in Punjab (25.6%) and followed by Haryana (21.2%), UP (25.3%) and MP (12.5%). However, Output-input energy ratio of CA practices in term of carbon emission was observed maximum in MP (2.0) followed by Haryana (1.9) followed by Punjab (1.5), UP (1.4).
References:


IPCC. Climate change: the scientific basis. Intergovernmental panel on climate change. Cambridge (UK): Cambridge Univ. Press; 2001.


The world is facing an impending water shortage that will complicate national and global efforts to alleviate and prevent food shortages in many regions. The increasing water scarcity resulting from population growth, rising incomes, and climate change, limits the amount of water available for food production and threatens food security in many countries. Water scarcity is a relative concept and there are various indicators and thresholds of water scarcity. Although the global amount of renewable fresh water has not changed, the amount available per person is much less than it was in 1950, due to population growth and increasing demands on available resources. Water is not equally distributed throughout the world and impacts of climate change will vary among regions. Among the regions that are conventionally (blue) water scarce, but still have sufficient green and blue water to meet the water demand for food production are large parts of sub-Saharan Africa, India and China. If green water (on current agricultural land) for food production is included, per-capita water availability in countries such as Uganda, Ethiopia, Eritrea, Morocco and Algeria more than doubles or triples. Moreover, low ratios of transpiration to evapotranspiration (T/ ET) in countries such as Bangladesh, Pakistan, India and China indicate high potential for increasing water productivity through vapour shift (Rockström et al., 2009).

India is an agrarian country with majority of population engaged and dependent on agriculture. Adequate water resources are instrumental in ensuring food security and affordability for whole of the society. India has made significant progress in development of its water resources over the past 60 years. The expansion of irrigation system alongwith modern agronomic practices has increased the production of food grains from a meager 51 million tonne in 1951 to more than 235 million tonne at present. Doubling land productivity in four decades from now could help India to meet most of its increasing food demand to about 380-400 million t by 2050 (Amarasinghe et al., 2007). But unlike four decades ago, water, a critical factor for crop production and other uses by humans and ecosystems, is also becoming scarce. The adverse impact of climate changes includes water crisis and an increased risk of extinction for an estimated 20 to 30 per cent of plant and animal species in India if the global average temperature exceeds 1.5 to 2.5 degrees Celsius. Climate change will exacerbate the impact of deforestation on water regulation. Although the Indus system is currently robust enough to cope with shortages of 10-13% in river flows, when the rivers flow drops to 15-20% below the average, irrigation shortages occur (Khan, 1999). Therefore, change in climate will affect the soil moisture, groundwater recharge and frequency of flood or drought episodes and finally groundwater level in different areas.

Increasing crop water productivity is a key response option where water is scarce compared with land and other resources involved in production. Improvements to agricultural water productivity (water productivity in crop, livestock and aquaculture production) help to meet rising demands for food from a growing, wealthier and increasingly urbanized population, when at the same time there are pressures to reallocate water from agriculture to cities and to make more water available for environmental uses contribute to the urgency for achieving gains in agricultural water management.

Water Productivity: Concepts

Water productivity is a measure of the amount of water needed to generate an amount (or value) of produce. The water productivity per unit of gross inflow (WPG) is the crop production divided by the rain plus irrigation flow. Because water productivity can be quantified it enables improvements to be charted, thereby encouraging faster progress (Passioura, 2006). Indeed, irrigation efficiency and water use efficiency are still useful parameters provided they are well
defined and used at the level of individual farmers or irrigation projects. ‘Water productivity’ can be quantified at higher scales, but its meaningful use is also conditional on unambiguous definitions. The main reason to improve agricultural water productivity (water productivity in crop, livestock and aquaculture production) is to meet rising demands for food from a growing, wealthier, and increasingly urbanized population, while there are pressures to reallocate water from agriculture to cities and to make more water available for environmental uses (Molden et al., 2009).

**Assessment of Water Productivity (WP)**

At present, WP of India is stubbornly low in comparison with other major foodgrain producing countries in the world (Molden et al, 1998; Rosegrant et al., 2002; Cai and Rosegrant, 2003). In 2000, WP of foodgrains in India was only 0.48 kg/m$^3$ of consumptive water use (CWU). This was primarily due to low growth in yields. India’s food grain yield was 1.7 tons/ha in 2000, which has increased only 1.0 tons/ha during 1960-2000 (FAO, 2005). Meanwhile, China with a similar level of yield (and soil-climate conditions) in 1960 (0.9 tons/ha) has increased to about 4.0 tons/ha by 2000. Also, India produces less grain in more cropped area (205 million mt in 124 million ha), while China has much larger production and with less water from a significantly smaller crop area. Indeed India has a significant scope for raising the levels WP by increasing its crop yield alone. Better water management can create additional increase in WP in many regions. Regional estimates show a significant spatial variation in WP across states and districts in India.

Livestock water productivity (LWP) can be defined as the amount of water depleted or diverted to produce livestock and livestock products and services, including energy. In computing LWP benefits from livestock, milk production, carcass weight, draught use, and manure values per unit of water used for raising the mix of livestock species owned by a household. Virtual water in the crop residue was accounted for, with reference to its relative value to that of grain, based on local market prices. In the context of water productivity, the amount of water depleted or diverted by livestock and for producing different livestock products is indirectly addressed but not accounted for in the water productivity equations by most authors (Kijne et al., 2003) or when it is accounted for, additional benefits by livestock are not included (Singh and Kishore, 2004). Livestock water productivity likely increases with an increase in the proportion of the volume share of crop residues in livestock feed to meet the annual requirement.

**Variations of water productivity among Indian states:**

Among different states, CWP (Table 1) varies from 1.01 kg/m$^3$, the highest in Punjab to 0.21 kg/m$^3$, the lowest in Orissa (Amarasinghe and Sharma, 2008). These differences are mainly due to varying cropping and land-use patterns, yield levels and CWU. Among the various states, significant differences are there. Punjab, Haryana, and Uttar Pradesh (UP) in the Indo-Gangetic basin (IGB) are having the highest water productivities. These states, with rice-wheat dominated cropping pattern, share 26% of the total CWU in India, but contribute to 40% of the total foodgrain production. Importantly, they contribute to 70% of wheat and 26% of rice production in India. A major part of area under foodgrain in these states is irrigated. It is 67, 85 and 97% in Uttar Pradesh, Haryana and Punjab, respectively, and contributing to 48, 72 and 75% of the CWU. West Bengal (WB), a major part of which is in the IGB, and Andhra Pradesh (AP), Tamil Nadu (TN), and Kerala in peninsular basins with rice-dominated cropping patterns, have moderate to high WP. Although irrigation contributes a major part of CWU in AP and TN, its contribution is low in WB and Kerala. Maharashtra, Madhya Pradesh (MP), Karnataka and Gujarat, with a mixture of cropping patterns (more than 50% of the area under maize and other coarse cereals and pulses) have lower WP. In Maharashtra and Karnataka, irrigation covers only 15 and 23% of area,
respectively, and contributes 17 and 28% of the CWU. Irrigation in MP and Gujarat covers 29% of the grain area, but contributes 52 and 41% of the CWU. Orissa, Chattisgarh and Jharkhand, have the lowest water productivities, and share 12.8% of the total CWU but contribute only 6.3% of the grain production. Rainfed rice dominates cropping patterns in these states.

The water productivity (WP) of all districts of the country varies from 0.11 kg/m³ to 1.25 kg/m³ (Figure 1). WP in the first to fourth quartiles varies from 0.11- 0.34, 0.34-0.45, 0.45-0.60, and 0.60-1.25 kg/m³. Districts in the fourth quartile of water productivities account for only 22% of total grain area and 22% of total CWU, but contribute 38% of total grain production. Irrigation provides water supply to 72% of the total grain area in this group, and contributes 60% of total CWU. In irrigated areas, irrigation accounts for a major part (72%) of total CWU. Districts in the first quartile of water productivity, however, account for 29% of total CWU and 30% of the total grain area. These districts contribute only 15% of total crop production. Effective rainfall, the main source of CWU in this group, accounts for 83% of total CWU

Strategies for Water productivity improvement

In the broadest sense water productivity targets at producing more food, income, livelihoods, and ecological benefits at less social and environmental cost per unit of water input, where water use means either water delivered to a use or depleted by a use. The basic principle for increasing WP might be obtained either through:

- Increasing the numerator (or yield) by bridging the gap between actual and maximum yield at present, or by providing additional irrigation or selecting appropriate crop choices in mainly rainfed districts.
- Decreasing the denominator (or CWU per unit land) without losing any yield or returns to a unit of water consumed.

Many promising pathways for raising water productivity are available over the continuum from fully rainfed to fully irrigated farming systems. These include supplemental irrigation (small irrigation to supplement rainfall), soil fertility management, deficit irrigation; small-scale water harvesting and storage, delivery and application methods, auxiliary storage in the canal command areas, precision irrigation technologies (as drips, micro-sprinklers, sprinklers); and soil and water conservation through mulching, zero or minimum tillage, bed planting and laser leveling. Some of the more recent and innovative techniques and policies for improving water productivity include the following:

Adequate and timely irrigation:

It is quite established that water stress in critical periods of crop growth is a key determinant of low yields in the rain-fed areas. With proper and timely application of a small quantity of additional irrigation in water stress periods by itself could reduce the yield gap, and additional irrigation with better application of non-water inputs could push up the average yield in parallel to the increasing path of maximum yield. Recent studies (Sharma et al., 2008) estimated that frequent occurrence of mid-season and terminal droughts of 1 to 3-weeks consecutive duration during the main cropping season happens to be the dominant reason for crop (and investment) failures and low yields. Provision of critical irrigation during this period had the potential to improve the yields by 29 to 114% for different crops.

Resource conservation technologies (RCTs):

There are many well known crop water productivity improvement measures including supplemental and deficit irrigation, water saving devices, soil conservation, soil fertility improvement and resource conservation technologies (RCTs) like zero tillage and bed planting. RCTs include zero tillage (or reduced/ minimum tillage), laser land levelling and furrow bed planting. Many studies have shown the effectiveness of RCTs in reducing water application, especially at field scale. The use of RCTs, including zero tillage, laser levelling and bed and
furrow planting, reduced water applications between 23% and 45% while increasing yield. With adoption of zero tillage in rice-wheat systems, water savings increases up to 30% (Hobbs and Gupta, 2003). Study showed 25% to 30% savings in irrigation water under zero tilled wheat compared to conventionally tilled (CT) in the rice-wheat belt of the Indo-Gangetic plains (Gupta et al, 2002). Similarly conservation tilled plots had higher (14–22%) soil moisture than conventional tillage irrespective of the cropping system, which has direct bearing on soil moisture recharge and its uptake by a crop (Ghosh et al., 2010). Study (Chandra et al., 2007) on water productivity under zero tillage and bed planting (BP) in rice-wheat system in the western IG plains at Pabnawa Minor of Bhakra Canal System in Kurukshetra, Haryana reported that wheat water productivity in bed planting method of crop establishment is generally higher than that under zero tillage and conventional tillage at plot level in different reaches. Water productivity of wheat in bed planting is greater than that under zero tillage and wheat water productivity in zero tillage is greater than that under conventional tillage across plot to watercourse scales. The irrigation water productivity for rice under BP is higher (22 to 28%) than that of CT but land productivity is lesser as compared to conventional tillage (Table 2). There is a trade-off between water productivity and land productivity in bed planted rice. Results of this analysis indicate the superiority of zero tillage over the conventional tillage both in terms of irrigation water productivity and land productivity in wheat besides profitability. Water productivity under n both zero tillage and conventional tillage decreases as one moves from plot level to watercourse level (i.e., for the three levels of analysis). Higher level of water productivity under zero tillage over conventional tillage at the farm and watercourse level suggests benefits of water saving under zero tillage at watercourse level.

**Auxiliary storage reservoirs in canal commands:**

Unreliable water supply in canal irrigation systems is often cited a major constraint for achieving higher agricultural and water productivity. It also constrains farmers to match water and other agro-input requirements during critical periods of crop growth, limit opportunities for crop diversification and also realise only sub-optimal yields. Unreliable water supply is often associated with rigidly or improperly implemented water delivery schedules in rotational water delivery systems such as Warabandi in north and north-west India and Pakistan. These water storage structures improve farmers’ control of on-farm water management and facilitated use of sprinklers for water application. An immediate impact of this was conservation of water and increased irrigable area. These storage structures and application systems can become a viable option for small land-holdings, provided they grow high-value crops (fruits/ vegetables) or diversify agriculture patterns to include fisheries in these tanks or use a shared resource to reduce the capital cost.

**Improving efficiency of irrigation systems:**

Water productivity in Banana was raised by 72 per cent in a dry-land watershed at Saliyur in Coimbatore district when conventional surface method of irrigation was replaced by drip irrigation. Water saving irrigation methods help in improving water productivity. Molden et al. (2007) have reported gains in water productivity varying from about 40% to over 200% for various crops (Banana, Sugarcane, Cabbage, Cotton, Grapes, Potato, Tomato) in shifting from conventional surface methods to drip irrigation in India. Water productivity of LEWA (Low Energy Water Application) device for wheat at Patna was estimated to be 1.91kg/m3 against 1.62 kg/m3 and 0.95 kg/m3 for sprinkler and surface methods of irrigation respectively.

Considering that under the prevailing policy and pricing systems in the developing countries the marginal and opportunity cost of available water is low, there are large gaps between water demand and supply patterns. In a study by IWMI in Pakistan Punjab (Jehangir et al, 2007) average input to rice was estimated as 1,458 mm against the potential water requirements of 532 mm. It resulted in low gross depleted fraction of 0.40 indicating about 60% of water was not used
in rice ET and mainly left root zone as seepage and deep percolation flows. In contrast farmers tend to under-irrigate the wheat crop and try to best utilise the rainfall. Besides the variation in crop to be irrigated, the source of irrigation water also has major role for conserving/saving water and thus improve the water productivity. Generally, irrigation with groundwater was found to be more efficient due to better control over the amount and timing and manageable flows. Improved methods of irrigation have large potential for water conservation and improved productivity. With drip irrigation, in most cases, water savings of 25-80% have been reported. At the country level, adoption of drip irrigation for suitable crops (Table 3) in the potential areas may lead to reduction in crop water requirements to the level of 44.46 BCM Kumar et al., 2008). However, the economic viability of micro-irrigation depends upon a wide range of factors including market rural infrastructure

**Integrated farming system approach for LWP improvement:**

Livestock water productivity is likely to increase with an increase in the proportion of crop residues in meeting the total livestock feed requirements. Integrated mixed crop/livestock farming systems offer ample opportunity to improve upon the existing very low level of productivity per head of animal. Integrating suitable multipurpose forage crops with existing farming systems will help increase supply of nutritious livestock feed, improve fertility of crop lands and minimize erosion of top soil. Promotion of community-based initiatives for improving utilization of communal grazing lands will further increase LWP. These initiatives will focus on practical ways of increasing communal pasture productivity through renovation of degraded grazing land and alleviation of the overstocking problem. This would ultimately bring about increased livestock productivity in a sustainable manner.

**Social awareness programme:**

There should be a holistic approach to teach individuals and organizations how to change their behaviour and stop wasting water. Water-efficient public behaviour can be promoted through such instruments as public campaigns to inculcate a shared vision of a prosperous and environmentally sustainable future. Another powerful way to reach a public audience is the formal education system, which can promote efficient water use with improved teaching materials, teaching training, experiential models and hands on project.

**Modelling approaches for improving CWP**

For better understanding of the global water-food relationship, it is necessary to provide accurate crop yield and crop water productivity (CWP, defined as the ratio of crop yield to actual evapotranspiration) data at a large scale and with a high resolution. However, traditional methods are not sufficient for estimating crop yield and CWP on a global scale given large spatial and temporal variations across different geographical locations. As the escalation of water scarcity and the integration of world economy, there is an emerging need to support water and food policy and decision making at the global and national levels.

A systematic tool that is capable of analyzing water-food relationships at high spatial resolutions would be very useful. The integration of GIS with a crop growth model can increase the range of applicability of the crop growth model. A GIS-based EPIC (Environmental Policy Integrated Climate) model developed (Liu et al., 2008) and tested to simulate crop yield and CWP by considering different factors such as climate conditions, soil properties, land use, water and fertilizer management etc. GEPIc was applied to simulate yield and CWP for maize on a global scale at a grid resolution of 30 arc-minute on the land surface. Similarly, another crop water productivity simulation model ‘AquaCrop’ developed by the Water Unit at the FAO, to simulate yield response to water of several herbaceous crops, and is particularly suited to make decisions, in conditions where water is a key limiting factor in crop production. It uses a relatively small number of explicit and mostly-intuitive parameters and input variables requiring simple methods.
for their determination. AquaCrop is a companion tool for a wide range of users and applications including yield prediction under climate change scenarios. It is mainly intended for practitioners working for extension services, governmental agencies, NGOs, and various kinds of farmers associations. There are some other basic models (SWAP, SWAT etc.) also available for water management, which can be applied for improvement in CWP.

**Epilogue**

Several promising pathways are available for raising water productivity over the continuum from rainfed to irrigated farming systems. Supplemental irrigation in the regions with low consumptive water use has the potential to double the existing yield levels. Analysis showed that by providing just one critical irrigation in 25 M ha of the potential rainfed areas the yield of most crops shall improve by 50% and the intervention is economically viable especially for rice, pulses and oilseed crops. Resource conservation technologies can help in realising water savings to the level of 20-45% at the field scale under most conditions. Improved irrigation systems as drip irrigation with better adoption rate and targeted subsidies has the potential to conserve about 44.5 BCM of irrigation water under Indian conditions. However, there are still some researchable issues, which are to be addressed in near future for achieving improved water productivity. The issues are:

- How can advances in information technologies help to develop better frameworks to analyze and predict water productivity in different agro-eco-systems?
- How can water productivity be maintained for crops under extended periods of mild water deficit and brief periods of severe water deficit?
- How can the integrated approach be practiced along with enhancing water productivity for livelihood security under climate change scenario?

**References**


Table 1. Variation in water productivity among the various Indian states

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<th>Yield (t/ha)</th>
<th>CWU (mm)</th>
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<td>11.1</td>
<td>0.99</td>
<td>278</td>
<td>0.36</td>
</tr>
<tr>
<td>3.</td>
<td>West Bengal</td>
<td>6.6</td>
<td>15.2</td>
<td>2.31</td>
<td>447</td>
<td>0.52</td>
</tr>
<tr>
<td>4.</td>
<td>Bihar</td>
<td>7.1</td>
<td>12.1</td>
<td>1.71</td>
<td>373</td>
<td>0.46</td>
</tr>
<tr>
<td>5.</td>
<td>Rajasthan</td>
<td>11.7</td>
<td>11.7</td>
<td>1.00</td>
<td>220</td>
<td>0.46</td>
</tr>
<tr>
<td>6.</td>
<td>Punjab</td>
<td>6.3</td>
<td>25.5</td>
<td>4.07</td>
<td>404</td>
<td>1.01</td>
</tr>
<tr>
<td>7.</td>
<td>Haryana</td>
<td>4.3</td>
<td>13.4</td>
<td>3.13</td>
<td>363</td>
<td>0.86</td>
</tr>
<tr>
<td>8.</td>
<td>Uttaranchal</td>
<td>1.0</td>
<td>1.7</td>
<td>1.75</td>
<td>298</td>
<td>0.59</td>
</tr>
<tr>
<td>9.</td>
<td>J&amp; K</td>
<td>0.9</td>
<td>1.2</td>
<td>1.38</td>
<td>271</td>
<td>0.51</td>
</tr>
<tr>
<td>10.</td>
<td>Himachal Pradesh</td>
<td>0.8</td>
<td>1.5</td>
<td>1.78</td>
<td>245</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>India</td>
<td>123</td>
<td>205.4</td>
<td>1.66</td>
<td>344</td>
<td>0.48</td>
</tr>
</tbody>
</table>


Table 2. Water and land productivity of bed planted rice and conventional tillage rice

<table>
<thead>
<tr>
<th>Locations</th>
<th>Method of sowing</th>
<th>Irrigation water productivity (kg/m³)</th>
<th>Gross water productivity (kg/m³)</th>
<th>Average yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pabnawa Head-end</td>
<td>Bed Planting</td>
<td>0.38</td>
<td>0.37</td>
<td>4.76</td>
</tr>
<tr>
<td>Pabnawa Middle 1</td>
<td>Bed Planting</td>
<td>0.39</td>
<td>0.38</td>
<td>5.43</td>
</tr>
<tr>
<td>Pabnawa Middle 2</td>
<td>Bed Planting</td>
<td>0.49</td>
<td>0.46</td>
<td>4.93</td>
</tr>
<tr>
<td>Pabnawa Tail-end</td>
<td>Conventional tillage</td>
<td>0.31</td>
<td>0.30</td>
<td>5.53</td>
</tr>
</tbody>
</table>

Source: Dinesh Kumar, M. and Amarasinghe U.A., 2008

Table 3. Aggregate reduction in crop water requirements possible with drip irrigation in India

<table>
<thead>
<tr>
<th>Name of crop</th>
<th>Water productivity (kg/m³)</th>
<th>Improved water productivity (kg/ m³)</th>
<th>Reduction in crop water requirement (BCM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane</td>
<td>5.950</td>
<td>18.09</td>
<td>31.00</td>
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<tr>
<td>Cotton</td>
<td>0.303</td>
<td>1.080</td>
<td>10.42</td>
</tr>
<tr>
<td>Groundnut</td>
<td>0.340</td>
<td>0.950</td>
<td>1.453</td>
</tr>
<tr>
<td>Crop</td>
<td>District</td>
<td>WP</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td>11.79</td>
<td>17.21</td>
<td>0.127</td>
</tr>
<tr>
<td>Castor</td>
<td>0.340</td>
<td>0.670</td>
<td>0.497</td>
</tr>
<tr>
<td>Onion</td>
<td>1.544</td>
<td>2.700</td>
<td>0.963</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>44.46</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: Kumar et al., 2008*

![District level WP across major states](image)

*Figure 1. District level WP across major states*

*Source: Amarasinghe U.A., and B. Sharma. 2008*
Soil Water Balance Modelling - SPAW model

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Indian Institute of Soil Science, Nabibagh, Bhopal-462038 (MP)

The concept of soil water balance is useful in understanding and modelling the flow of water in the soil-plant-atmosphere chain. The universal principle of movement of water, be it in soil, plant or atmosphere, is the flow taking place from a region with higher potential energy state to a lower state. The various models of soil water dynamics basically employ the energy and water balance concepts.

**Soil water balance**

The water balance is based on the law of conservation of mass, which states that matter can neither be created nor destroyed but can change from one state or location to another. In simplest terms, the water balance merely states that any change that occurs in the water content \( \Delta w \) of a given body of soil during a specific period must equal the differences between the amount of water added to that body, \( W_{in} \), and the amount of water withdrawn from it, \( W_{out} \), during the same period:

\[
\Delta w = W_{in} - W_{out}
\]

The root zone water balance is usually expressed in the following form:

\[
\Delta S + \Delta V = (P + I + U) - (R + D + E + T)
\]

Where, \( \Delta S \) is change in root zone soil moisture storage,

\( \Delta V \) is the increment of water incorporated in vegetation biomass

\( P \), precipitation; \( I \), Irrigation; \( U \), upward capillary movement into the root zone; \( R \) runoff;

\( D \), downward drainage out of the root zone; \( E \), soil evaporation; \( T \), transpiration

**Soil water balance modelling**

Modelling soil water dynamics requires defining the scale and the associated hydrologic and hydraulic processes in a particular system. The scale may vary from a field to a watershed or a catchment. Accordingly, the relative importance of the involved processes are different. For instance, in a field based model, evapotranspiration is more important whereas in a watershed based model, runoff is a major component of water balance. The commonly used soil water models in the field of agriculture and soil water management are:

1. SWAT (Soil and Water Assessment Tool) model
2. SWAP (Soil-Water-Atmosphere-Plant) model
3. SPAW (Soil-Plant-Atmosphere-Water) model
4. WEPP (Water Erosion Prediction Project) model
5. EPIC (Erosion Productivity Impact Calculator) model
Apart from the exclusive soil water balance models, various crop growth simulation models such as CERES, WTGROW for wheat, ORYZA for rice, CROPSYST, APSIM, GOSSYM for cotton, PEANUTGRO for ground nut etc have water balance modules to simulate the processes of water dynamics inside the soil – plant-atmosphere system.

The SPAW model

The Soil-Plant-Atmosphere-Water (SPAW) model has been developed by K.E. Saxton (1981) of USDA for simulation of daily hydrologic budgets for field and inundated water bodies such as ponds. The model computes daily hydrologic budgets for agricultural fields with a moderate level of complexity to account for the most important hydrologic processes. Inputs describe the climate, soil and crops of a farm field in the one dimensional vertical plane. The principal hydrologic inputs are daily rainfall and potential evaporation, with optional daily maximum and minimum air temperatures. Soil and crop descriptions determine the daily disposition of this water into and out of the soil-plant-air-water (SPAW) system. Recent enhancements to SPAW were the addition of an irrigation field (scheduling) module and an inundated pond module.

The objective of the SPAW model development was to predict agricultural field hydrology and its interactions on crop production using medium range technical complexity while minimizing input data and computation time. The SPAW model has been applied extensively to hydrologic simulations for both research and design. The original versions were focused on plant available soil water under rain-fed conditions. Subsequent versions have provided significant model additions, alterations, added capability and numerous application evaluations related to agricultural field hydrology.

The most recent additions were an irrigation scheduling methodology and a POND module that utilizes daily SPAW field hydrology analysis to simulate daily pond inflow, outflow and storage. Auxiliary inflows and withdrawals from the pond allows for the simulation of a variety of pond functions such as seasonal and permanent wetland ponds, irrigation storage reservoirs, animal waste storage ponds, and ponds used for livestock water supplies. This lecture note shall focus on the SPAW – field model only.

Hydrologic Processes Represented

Field model: The principal hydrologic processes considered in the SPAW field model are the following as depicted in Figure 1 by a schematic of the vertical water movement of a field:

Precipitation: daily totals including snow accumulation and melt when air temperature data are included.
Runoff: Estimated by the USDA/SCS curve number method modified for daily soil moisture and vegetation conditions. Frozen soil effects are included if air temperature data are included. No stream routing is provided.
Infiltration: A daily amount based on precipitation minus estimated runoff which infiltrates into the upper-most soil layers as storage is available.
Redistribution within the soil profile: Infiltrated and existing soil water is moved between defined soil layers by a Darcy tension-conductivity procedure providing either downward or upward flow.
Evapotranspiration: Daily estimates of plant transpiration, direct soil surface evaporation and surface interception evaporation estimated by a daily potential evaporation reduced by the current plant and soil water status. Potential evaporation data are derived externally by any one of several methods such as the Penman and/or Monteith method, daily pan evaporation, daily temperature or radiation methods or mean annual evaporation distributed as monthly mean daily values.
**Percolation:** Daily water leaving the bottom of the described soil profile which will contribute to local ground water or horizontal inter-flow.

![Diagram](image)

**Fig.1** The major hydrologic processes considered in the SPAW-field model

**Data Inputs and Sensitivities**

**Climatic Data**

1. Precipitation and/or irrigation on daily basis
2. Evaporation (Potential ET) on daily basis
3. Daily maximum and minimum air temperature (optional)

The principal driving forces and most sensitive factors in the SPAW model are precipitation and the evaporation or potential evapotranspiration (PET). Daily values are the most appropriate input for the SPAW model for a daily time-step hydrologic simulation. Values for each day are important and these data should be carefully checked for obvious errors and missing values, particularly for precipitation.

Climatic data may be used from a nearby local source if they are not available at the simulation site. Thus the impact of spatial variation must be assessed and recognized to evaluate the simulation results. Evaporation and air temperature data are not as spatially or temporal variable as precipitation data, and therefore can often be transferred some distance or estimated by time-averaged weekly or monthly values and yet provide reasonable results.

**Soil Profile data**

- Soil texture (Layer wise)
- Soil water retention constants, layer wise (WHC, Field capacity, PWP)
- Soil organic matter content, layer wise
- Soil depth
- Maximum rooting depth
- Soil water transmission characteristics (conductivity, diffusivity etc)
- Thickness of evaporative and image layer

The soil profile is described by incremental layers and water characteristic curves for each layer. Except for the upper and lower boundary, the layers should reflect the soil profile changes and provide an incremental soil water profile to allow appropriate calculations and definitions. Usually, smaller increments (10 to 20 cm) are used in the first 60 to 100 cm below the surface. Thinner layers are not warranted and cause excessive computations while large layers provide excessively broad averages.

The upper boundary (evaporative) layer is considered to be a very thin layer (1.0 inch) which rapidly dries with no resistance as in stage-1 soil water evaporation. It re-wets to near saturation by precipitation and dries to a percentage near air dry. The lower boundary (image)
layer is specified below the last soil layer with water characteristics the same as the last layer and a specified thickness. This layer controls deep percolation or upward-flowing water back to the profile. When the water content of the image layer exceeds a specified percentage of its field capacity, water is cascaded downward to become groundwater recharge and is lost from the control volume. If the last real layer becomes drier than the image layer, water is conducted upward from the image layer into the profile, thus it serves as temporary profile water storage.

**Crop Characteristics**

- Per cent canopy cover
- Greenness per cent
- Root water extraction pattern
- Yield susceptibility
- Annual N uptake (optional)

Canopy values can be derived by measurements or visual estimates of soil shading. The model is not highly sensitive to these values, and seasonal distributions of even fast-growing crops provide reasonable results. Measured leaf area index (LAI) is a common measured descriptor which can readily be related to canopy cover by a relationship.

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The maximum root depth throughout the calendar year is described as date-depth data points. The rooting density and effectiveness for water uptake is partitioned for each 25% of the maximum depth by the 40-30-20-10 percentage as the maximum depths are interpolated between the input data points.

**Field Management**

The two major field management data inputs are the time and amount of irrigation and application of fertilizers (N). An irrigation scheduling routine is specified with choices for the time, depth and method of irrigation for each crop/year.

**Other input data**

It is often useful to include initial or measured data for the simulated variables such as runoff, soil water, or one of the chemical species. These optional input data by soil profile layers include:

- Soil moisture content
- Runoff,
- Salinity,
- Nitrate-N,
- Ammonium-N,
- Negative ion chemical tracer (like nitrate without plant uptake, eg. Cl, Br).

The simulation output includes these data used as either a comparison with simulated values or to reset the simulation to be equal to the input data such as for initialization. Standard tabled curve numbers for daily runoff estimates are shown based on the selected soil and crop parameters, or an alternative set of curve numbers can be manually entered.

**Output parameters**

- Layer wise soil moisture (volumetric) content
- Actual ET
- Soil evaporation
- Runoff
- Deep percolation
- Crop biomass and yield

Most of the studies involving SPAW model have simulated the soil moisture and actual evapotranspiration, both under non-crop and crop conditions. A schematic flow diagram is given below (Fig.2) showing the various pathways by which the PET is reduced to actual ET after accounting for interception, evaporation, redistribution and movement processes during the simulation process.

Fig. 2 C. Schematic of actual ET and soil moisture redistribution

Limitations and Ranges

1. The SPAW model is a field scale, vertical water budget, given that the field can be considered spatially uniform in soil, crop and climate. These considerations limit the definition of a “field” depending on site conditions and the intended simulation accuracy.

2. The SPAW model is not intended for watershed hydrologic analyses, since each simulation is tied to a specific set of soil, crop and climate data. However, it could be utilized for relatively small watersheds composed of multiple farm fields, each simulated separately and the results combined. There is no stream flow routing or channel descriptors included and daily runoff is estimated as an equivalent depth over the simulated field.

3. The POND model allows for a combined field concept to represent watershed input for inundation simulations of wetlands and ponds. The total combined area of fields used in POND simulations should adhere to maximum limits established for the SCS Runoff Curve Number process, approximately 800 ha.
4. The POND model has minimal limitations of size, shape or volumes. However, the climatic and watershed representations limit the practical application to maximum pond sizes in the range of 40 to 80 ha.
India with a geographical area of 329 Mha presently supports 17% of the global population on merely 2.5% world’s land area and 4% fresh water resources. Moreover, one billion plus population is expected to reach 1.4 billion by 2025 requiring about 310 Mt of food grains (compared to about 200-210 Mt at present) with a projected linear decrease in per capita land availability from 0.34 ha in 1950-51 which is likely to come down to 0.12 ha by the year 2025 (Suri, 2007). The net cultivable area in the country is about 140Mha is remaining constant or even squeezing from the pressures of urbanization, industrialization, infrastructure development and to house the ever increasing population. The loss of productive soil is another concern. The loss of fertile top soil by water erosion is estimated to be about 5334 Mt per year with it nearly 6 million tonnes (Mt) of nutrients due to ill soil and water management practices. The latest estimate by NBSS&LUP, Nagpur using Global Assessment of Soil Degradation (GLASOD) guidelines, indicates 187.8 Mha of land degraded by various degrees and by various degradation processes.

The annual water erosion rate varies from less than 5 t/ha in arid region of Rajasthan to more than 80 t/ha in Shiwalik hills (Singh et al, 1992).

Both current and future climate risks are of greatest concern to farmers as well as to policy-makers as they plan to meet development needs. Climate change is affecting the rainfall distribution which creates the flood and drought condition in the country. The emerging patterns of climatic hazard risk are associated with climate change. It is expected, that global warming will enhance the hydrologic cycle, lead to heavier rainfall events and more severe droughts. Wind erosion is most severe in arid zones due to poor ground cover. By increasing deforestation and precipitation changes affect the water erosion from agricultural cropland. Climate change is the major challenge now a day and climate-related disaster risk is increasing. Hydro-meteorological hazards (droughts, floods, wind storms, forest fires or landslides) have significantly increased in recent decades. Extreme climate events regularly affect multiple sectors including agriculture, food security, water resources and health. Climatic variability can cause crop failures, shortages of water for irrigation, food insecurity and hunger. Impacts of extreme events such as droughts, floods and cyclones frequently accumulate into set backs of development gains and towards achieving the improvement in related to poverty, hunger and human health. Provision of appropriate forecast products with relevant impact, better informed policy guidance and locally adapted management alternatives which match the farmer’s needs help to reduce the negative impacts of climate change significantly. Soil and water are the most critical basic resources which must be conserved as effectively as possible. Soil and water conservation is the only known way to protect the lands from degradation and conserving rain water for improving the productivity of dry land crops.

**Soil erosion:** Soil erosion is the process of detachment of soil particles from top soil and transportation of the detached soil particles by wind and water. The detaching agents are falling raindrop, channel flow and wind. The transporting agents are water and wind. There are two type of soil erosion namely water and wind erosion. Sheet, rill, gully, ravine, land slide and stream bank erosion are represent the water erosion. Wind erosion occurs by process of saltation, suspension and surface creeping in arid zones.

**Factors affecting the water erosion**

Rainfall, vegetation, topography and soil types are important factors that influence water erosion under different regions.
1. **Rainfall:** Rainfall influences both the process of detachment and transportation. Amount, intensity, duration and distribution of rainfall influence runoff and erosion. It has great effect on the runoff. If the rainfall intensity is greater than infiltration rate of soil then runoff starts immediately after rainfall. While in case of low rainfall intensity runoff starts later. Thus high intensities of rainfall yield higher runoff. If the rainfall amount is greater than infiltration rate of soil then runoff starts immediately after rainfall. It is directly related to the volume of runoff because infiltration rate of soil decreases with duration of rainfall.

2. **Vegetation:** Among the different factors that influence erosion, vegetative cover is most important. The impact of rain drops is absorbed by vegetation present on the soil surface and therefore, there is no break down the soil aggregates. In addition, the plant roots bind the soil particles. Due to addition of organic matter by vegetation, stable aggregates are formed which resistant to break down. Soil erosion is therefore, less under vegetative cover. The nature of vegetative cover on the soil surface such as crops, cropping system and the accompanying vegetation is the major factor influencing runoff. In addition, the root systems as well as organic matter in the soil increase the soil porosity thus allowing more water to infiltrate. Vegetation also retards the surface flow particularly on gentle slopes, giving the water more time to infiltrate. In conclusion, an area densely covered with vegetation, yields less runoff than bare ground.

3. **Topography:** The topography is the most important character that influences runoff and sediment transport. The land slope, its degree and length are important in determining the extent of soil erosion. Higher the degree of slope and more its length, more is the soil erosion due to increased velocity of the water flow is doubled, its erosive power increase four times and carrying capacity 64 times.

4. **Soil type:** The soil physical properties like soil structure and texture influence both detachability and transport of soil particles. Soil with stable aggregate are resistant to detachment. Light soils like sandy soil and sandy loams are easy to detach, but difficult to transport as the particles are heavy. In addition, the infiltration rate is high in light soils and runoff is less. With higher clay content of heavy soils, detachment is difficult, but transport is easy because most of the particles are light in weight. The infiltration rate is also less unless these soils have deep cracks. In general, runoff and soil loss increases with increasing fineness of the soil texture. The highest infiltration capacities are observed in loose, sandy soils while heavy clay or loamy soils have considerable smaller infiltration capacities. Moist soils are more susceptible to water erosion than dry soil because of higher runoff. Magnitude of runoff yield depends upon the initial moisture present in soil at the time of rainfall.

**Factors affecting the wind erosion**

Wind erosion is serious problem in areas where land is bare and devoid of vegetation. It is natural phenomena in arid and semi-arid zones. Wind picks up lighter particles, lift them from the surface and transport them long distance. The important factors that influence wind erosion climate, soil and vegetation, field length and topography.

1. **Climate:** The climate factors influencing wind erosion are wind velocity in addition to temperature and rainfall. Wind velocity is primary agent of wind erosion. Temperature and rainfall influence wind erosion through their effect of soil moisture. Soil moisture decreases wind erosion. Increase in soil moisture content decrease wind erosion. Moisture of 75% of field capacity there is no further influence of wind erosion.

2. **Soil:** Soil factors influencing wind erosion are texture, structure, cohesiveness, bulk density, organic matter and surface roughness. The moist erodible particles are about 0.1 mm or less in diameter. Soils with large aggregate and those with surface crust are rather resistant to erosion. Wind erosion is more from a fine, flat, bare land than from a rough soil surface.
3. **Vegetation:** The primary cause of wind erosion is depletion or destruction of vegetation or vegetative cover on land. Vegetative factors affecting erosion are height and density of cover, type of vegetation and its seasonal distribution.

4. **Tillage:** Tillage can influence wind erosion by disturbing the soil surface, causing dislodged particles to be more susceptible to transport by wind. Wind erosion during tillage is most severe when soil moisture is low but wind erosion is less under minimum tillage and optimum soil moisture content. Fine textured soils predominate. In addition, tilling on steep slopes may result in considerable soil losses.

**Control conservation measures of water and wind erosion**

Soil and water conservation is a combination of all management and land use practices which protect the soil against depletion or deterioration by natural or man – induced factors and improve the productivity of the natural resources on sustain basis. The soil and water conservation is not only anti-erosion and anti-runoff approach; it is a comprehensive and integrated approach for judicious use of these resources rather than their negligent and wasteful use. Water erosion occurs simultaneously in two steps that is detachment of soil particles by falling raindrop and transportation of detached soil particles by flowing water. Therefore, the principles of water erosion control are: Maintenance of soil infiltration capacity, soil protection from rainfall, control of surface runoff and safe disposal of surface runoff. The aim of soil conservation is to obtain the maximum sustained level of production from the land, while maintaining soil loss below threshold level. Since erosion is a natural process it cannot be prevented but it can be reduced to an acceptable level. The strategy of soil conservation is based on covering the land surface to prevent it from raindrop impact, increasing infiltration capacity of the soil to reduce runoff, improving stability of soil aggregate to reduce splash and entering of soil particles and increasing land surface roughness to reduce the amount of the velocity of runoff water.

By adopting minimum tillage and maintenance of permanent soil cover that can increase soil organic matter and reduce impacts from flooding, erosion, drought, heavy rain and winds. Enhancing residual soil moisture through land conservation techniques assists significantly at the margin of dry periods while buffer strips, mulching and zero tillage help to mitigate soil erosion risk in areas where rainfall intensities increase. Control measures of water and wind erosion are the best management practices leading to profitable crop production without land degradation. The following soil and water conservation measures may be adopted for controlling the soil erosion depending on the degree and length of the slope and physical configuration of the land.

1. **Agronomical measure:** The agronomic measures include covering soil surface by mulching, growing cover crops (cowpea, moong-bean and grasses) pasturing and rotation grazing, strip cropping and multiple cropping. Agronomic measures help to reduce kinetic energy of rain drops as well as of runoff water. Row crops (maize, oat) are least effective and therefore they must be combined with protective crops in a logical cropping pattern to reduce soil erosion. Legume-cereal, legume -fodder and legume-grass rotations are effective erosion control measures. The following crop management practices can be useful in minimizing the soil erosion, soil and nutrients losses.

   - **Cropping system:** Crops with the ability to develop quickly provide an early protection of soil. Inter planting of erosion-resistant crops like cowpea, soybean etc. is also useful. Strip cropping of erosion –resistant legume along with cereals can conserve rain water and reduce the velocity of runoff.

   - **Crop geometry:** It is essential to manipulate the crop layout in the field in a manner which may prevent soil erosion. A closer spacing of rows across the slope can help in this regard.
Contour cultivation: Contour cultivation reduces the runoff to a large extent, thereby reducing the soil and nutrient losses. Contour cultivation as well as furrow and ridges have been found useful.

Tillage: Low intensity tillage favours consolidation of soil through better structure, infiltration and pore distribution. This imparts erosion resistance. A study of conventional method of cultivation of maize with zero tillage with or without live mulch has shown that runoff and soil loss are greatly reduced with low intensity tillage (Bhardwaj, 1998).

Agroforestry: Agroforestry has become popular as a useful land use system on slope in the recent past. Growing of trees along with agricultural crops satisfy multifarious needs of the farmers. Growing of multipurpose tree species is recommended with crops.

Grasses: Grasses are perhaps the best friend of soil conservationist. Low and evenly distributed canopy and fibrous root systems with much soil binding capacity make grass highly effective in controlling soil erosion. The performance of various grass species in controlling soil erosion and runoff losses at 9 and 11 % slopes.

2. Mechanical measure: Mechanical field practices are used to control the movement of water over the land surface. The practice depends on whether the objective is to reduce the velocity of the runoff water or to increase surface water storage capacity or to safely dispose of the excess water. Mechanical measures are normally used in conjunction with agronomic measures. The various mechanical measures are given below:

- **Contour Bunds**: contour bunds are mechanical barrier built across the slope for safe diversion of excess runoff and retaining eroded soil. Land area in between the two bunds gets leveled in due course of time. Due to deposition of eroded soil along the bund, latter takes the shape of riser. These risers should be planted with grasses to check their erosion.

- **Graded Bunds**: The graded bund is a small earthen bund with slight grade constructed across the slope for safe disposal of runoff. The graded bunds are recommended up to 10% slope for area where annual rainfall exceeds 800mm, particularly on clayey and black soils with poor drainage. The purpose of graded bunds is to reduce the velocity of runoff water, for in situ conservation of rain water and to minimize the soil erosion.

- **Bench terrace**: bench terrace are flat beds constructed on hills across the slope. The height of the riser should not be more than one meter and width of bench terrace depends on the degree of slope. The bench terrace are important because they promote uniform distribution of soil moisture, irrigation water, etc. and control, soil erosion. The bench terrace, may, be table, top, (level), outward, sloping, or inward sloping with or without mild longitudinal grades. On steep slope, it is better to constructed terrace on foothills for agricultural crops when soil dept is more than one meter.

- **Half moon terrace**: half moon terraces are semi circular beds of appropriate diameter with shape resembling a half moon. These terraces are recommended for fruit trees or other plantation crops on steep slopes.

- **Grassed water ways**: Grasses are well known for their soil binding characteristics. They are most effective in moderating the flow and reducing the erosive velocity of runoff, particularly on rolling topography. The runoff water moves with high velocity down slope, carrying with it soil and nutrients. If some suitable grasses are planted on the runoff route or natural channels, the soil and nutrients losses can be reduced. These grassed water ways are laid on natural drainage lines in the watershed.

- **Water harvesting ponds**: Water harvesting structures can be dug out for retaining runoff on seasonal pr perennial basis. These are generally constructed down the slope .the earthen dams
should be used for retaining silts loads at appropriate locations on the slope of watershed. The water harvested or stored can be used for supplemental irrigation.

- **Conservation bench terrace (CBT):** These are used to stabilize the yield of rainfed crops by inter-field water harvesting. A part of the filed is leveled to retain runoff originating from rest of the field.

- **Gully control structures:** Gully control structures are provided to reduce the erosive velocity of runoff, to facilitate establishment of vegetation or to provide protection at points that cannot be adequately protected by other methods. Loose boulder check dam perform well in gullies which do not carry much runoff and it also helps in silt deposition, thereby helping the stabilization of gully beds. Permanently gully control structures are constructed to control the over falls either at gully head or in gully bed.

- **Contour trenches:** Contour trenches are dug out, piling up the dug out earth on lower side of the trenches, for trapping sediment and runoff at early stage of their movement. These trenches also improve soil moisture and favour quick growth of tree and grasses.

3. **Agronomical-Mechanical measures:** Depending upon the needs of land and intensity of erosion, bio-engineering measures are some times preferred as compared to either mechanical or agronomical measures in isolation. In black soils with 40-50 % clay both agronomical and mechanical measures have been found to reduce runoff and soil losses. These conserve soil moisture and thereby increase crop yield. The treatment of vertical mulch and surface mulch has been found to be most effective in controlling runoff and soil losses and consequently, could produce maximum sorghum grain yield. Under mechanical measures, the graded bunding has been found to be superior to conservation ditch and contour bunds.

**Management practices of soil water conservation in different regions of India**

Soil conservation is using and managing land based on the capabilities of the land itself, involving the application of best practices to result in greatest profitable production without damaging the land by adopting land sue based on its capability, conservation of soil moisture to avoid damage of the soil and use of best soil and crop management practices. The semi arid tropics are mostly characterized with red and black soils. The problems associated with different soil types are different in physical, chemical and hydrologic terms. The red soils have low water holding capacity, high infiltration and crustung tendency. In black soils even though the water holding capacity is high, low infiltration rate results in greater loss of soil and rainwater. Accelerated runoff and soil erosion, surface sealing and crustung, low soil organic carbon content, and low inherent soil fertility are among major factors responsible for low crop yields from these soils. Vertisols are potentially productive soils within the semi-arid tropics of peninsular India. These soils have high water holding capacity. Major soil-related constraints in Vertisols include low water infiltration, high incidence of inundation, accelerated runoff and soil erosion during high rainfall year and drought stress during the low rainfall year. Vertisols of the semi-arid tropics in India have a fairly high potential for crop production when improved soil and water conservation practices.

Improving soil surface conditions to increase infiltration and improving water holding capacity are two basic requirements in dry lands. The inter-terrace management practices for in situ conservation of rain water and ensuring its uniform distribution within the filed and throughout the crop growth period assume paramount importance in dry land crop production. This can be achieved with appropriate tillage and in situ rainwater conservation practices at farm level. Soil water conservation measures can be adopted in different locations of country namely as tillage practices, vegetative barriers, mulching, cover crops, land configuration, cropping system, residue management and soil amendments are given below.
1. Tillage: Cultivation of soil helps to increase pore space and keeps the soil loose so as to maintain higher level of infiltration. Cultivation of surface greatly enhanced water intake of the soil particularly in the beginning of storms. In the absence of cultivation, the highly crusting red soils produce as much or even more runoff than the low permeable vertisols under similar rainfall situations. Bhardwaj (1988) revealed that reduced runoff and soil loss by 31.7 and 23.8 per cent, respectively under zero tillage as compared to conventional tillage in maize which produced 61.2% runoff and 15.76 t ha\(^{-1}\) soil losses at 4% land slope at Dehradun. Different tillage operations are carried out to incorporate crop residue, conserve the rain water in situ, recharge soil profile, prepare smooth seed bed for greater seed germinate with better root system, to reduce conserved soil water loss and its efficient utilization and control weeds/pests or disease and increase the crop yield (Patil, 1998 and Thyagaraj, 1999). In general, tillage operations make the soil receptive to rainfall through increased infiltration rate. Channapa, 1994) reported that the deep tillage with plough followed by chiseling opens the hard layers and increase the infiltration rate and water storage capacity and finally results in better crop growth with higher yields in the red soils at Bangalore (Table 1). Similarly in red soils in the farmers field at Coimbatore, the deep ploughing with chisel plough + disc plough + cultivator increased the soil water in the profile at different stages of sorghum growth as compared to soil cultivation with cultivator once or twice reduced tillage operations (Manian et al., 1999).

Table 1: Soil water storage in the profile as influenced by deep tillage in red soils

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Ploughed area (%) after 81 mm rainfall</th>
<th>Unploughed area</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>10.74</td>
<td>3.59</td>
</tr>
<tr>
<td>15-30</td>
<td>13.22</td>
<td>7.13</td>
</tr>
<tr>
<td>30-60</td>
<td>12.27</td>
<td>8.59</td>
</tr>
<tr>
<td>60-90</td>
<td>13.33</td>
<td>Dry</td>
</tr>
</tbody>
</table>

(Channapa, 1994)

The residue management represents only minor part of the cropping system, reduced/minimum tillage concepts are at a disadvantage in dry land cropping. It also observed that deep tillage reduced runoff, soil loss and increased the soil water in the red soil profile with increased sorghum yield by 26% over the normal tillage in alfisol soil at ICRISAT, Hyderabad (Table 2).

Table 2: Effect of normal and deep tillage on runoff, soil loss and sorghum yield

<table>
<thead>
<tr>
<th>Tillage practices</th>
<th>Runoff (mm)</th>
<th>Soil Loss (t ha(^{-1}))</th>
<th>Sorghum yield (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal tillage</td>
<td>285</td>
<td>3.27</td>
<td>2160</td>
</tr>
<tr>
<td>Deep tillage</td>
<td>195</td>
<td>2.86</td>
<td>2720</td>
</tr>
<tr>
<td></td>
<td>44.0</td>
<td>0.70</td>
<td>386</td>
</tr>
</tbody>
</table>

In vertisol, the effect of tillage was more pronounced in terms of rain water conservation and recharge of soil profile especially during drought years as compared to normal and above normal rainfall situation. In the deep black soils of Bijapur, Karnataka, deep tillage conserved higher amount of soil water in top 0.6 meter soil depth as compared to medium and shallow tillage from sowing up to harvest in winter sorghum. Higher soil water with deep tillage was attributed to increased infiltration rate and decreased bulk density. This results in better development of root and shoot in winter sorghum with deep tillage. Deep tillage recorded higher sorghum yield over medium and shallow tillage (Table 3).

Table 3: Effect of tillage practices on soil properties and grain yield of winter sorghum

<table>
<thead>
<tr>
<th>Tillage practices</th>
<th>Infiltration</th>
<th>Bulk</th>
<th>Root</th>
<th>Grain yield (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Channapa, 1994)
Table 4: Effect of vegetative barrier on runoff, soil loss and sorghum grain yield (Av. of 8 yrs)

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Slope</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Runoff (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up and down cultivation (control)</td>
<td>49.65</td>
<td>54.81</td>
</tr>
<tr>
<td>Vegetative barrier</td>
<td>22.69</td>
<td>39.86</td>
</tr>
<tr>
<td>Soil Loss (kg ha(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up and down cultivation (control)</td>
<td>1053</td>
<td>2167</td>
</tr>
<tr>
<td>Vegetative barrier</td>
<td>500</td>
<td>1372</td>
</tr>
<tr>
<td>Grain yield (kg ha(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up and down cultivation (control)</td>
<td>911</td>
<td>685</td>
</tr>
<tr>
<td>Vegetative barrier</td>
<td>1149</td>
<td>848</td>
</tr>
</tbody>
</table>

Table 5: Winter sorghum yield as influenced by moisture conservation practices

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Grain yield (kg ha(^{-1}))</th>
<th>Straw yield (kg ha(^{-1}))</th>
</tr>
</thead>
</table>

2. Vegetative barriers: Traditional mechanical bunds like contour and graded bund are effective in reducing runoff and soil loss. At some places due to poor maintenance these bunds have flattened over the years and became ineffective in conserving rainwater. Hence, research efforts have, therefore, been directed to develop vegetative measures to supplement mechanical measures. Vegetative barrier would act as a barrier and reduce velocity of water flow, filter and retain more silt, arrest the soil erosion. In combination with earthen bunds or loose bounder structures, vegetative are more effective in conservation of natural resources and increasing crop productivity. In black soil of Deccan Plateau at Bellary, the vegetative barrier proved effective in conserving soil and rainwater and increasing the soil water availability in the profile. The increased water availability has resulted in the better plant growth with increased grain yield of winter sorghum by 35% over the control. The vegetative barrier reduced the runoff by 36% and soil loss by 41% over the control with 100 mm rainfall (Table 4).

3. Mulching: Mulching is covering of the cultivated field with unused organic matter (grown in situ or ex situ) with little additional investment. Mulches are the important organic materials that not dissipate the kinetic energy but also facilitate infiltration and reduce runoff and evaporation losses. Besides, this has the major advantage of (i) Suppressing weed growth by preventing penetration of sunlight to the ground (ii) conserving soil and rainwater in situ. Thick mulch spread over the field conserve moisture in the soil, reduces evaporation loss and improves the water holding capacity of the soil. Mohan Rao et al, (1995) reported that as a result supplemental water demand of the crop is reduced. Application of surface mulch at sowing was found to have profound positive effect on grain and straw yield (Table 5).Crop residue such as sorghum and maize stubbles, dry grass, wheat straw and pigeon pea stalk can be used as surface mulch. These mulches prevent moisture loss and prolong the moisture retention period (Table 6). In Vertisol at Solapur, crop residue incorporation increased yield by 50 to 70 per cent. Lal (1980) reported that the runoff and soil loss decrease exponentially with an increase in mulch rate under 10% slope (Table 7).
Control & Surface mulch

Vertical Mulch (4m) + surface mulch

Mohan Rao et al, 1995

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Grain yield (t ha⁻¹)</th>
<th>Straw yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.72</td>
<td>3.43</td>
</tr>
<tr>
<td>Sorghum stubble (5t/ha)</td>
<td>1.02</td>
<td>4.49</td>
</tr>
<tr>
<td>Red gram stalk (5 t/ha)</td>
<td>1.21</td>
<td>5.52</td>
</tr>
<tr>
<td>Wheat straw (5 t/ha)</td>
<td>1.04</td>
<td>5.34</td>
</tr>
<tr>
<td>Dry grass (5 t/ha)</td>
<td>1.22</td>
<td>5.75</td>
</tr>
</tbody>
</table>

Patil et al. 1981

<table>
<thead>
<tr>
<th>Mulch rate (t ha⁻¹)</th>
<th>Runoff (% of rainfall)</th>
<th>Soil loss(t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17.4</td>
<td>9.6</td>
</tr>
<tr>
<td>2</td>
<td>10.0</td>
<td>2.3</td>
</tr>
<tr>
<td>4</td>
<td>3.5</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Lal (1980)

4. Land Configuration: Land configuration of the inter bund area can be modified for temporary inter plot harvesting of water and facilitate higher infiltration. These modified configurations could be implemented prior to or after the onset of monsoon and continued till sowing or even adopted after sowing and maintained till harvest.

A. Compartmental bundling: Compartmental bunding is usually adopted deep black areas for in situ harvesting of rain water. The field is laid out into compartments of 6m x 6m to 10m x 10m using bund former. The harvested water in these compartmental facilitates high infiltration rate resulting in more soil water retention in the profile. This system adopted in deep black soil to harvest rainwater during the rainy season. It helps in better crop production during the post rainy season. Patil (2005) indicated that the moisture conservation through in situ moisture conservation practices like compartmental bunding and ridge and furrow increased the soil water in the profile and grain and straw yield of winter sorghum on vertisol at Bellary, Karnataka (Table 8). Similarly in Vertisol at Coimbatore, (Selvaraju and Balasubramanian (2001) reported that compartmental bunding and Broad bed furrow have effective in conserving sufficient soil moisture support crop growth even during drought situation. In low rainfall year, compartmental bunding stored higher moisture and it led to favourable micro climate and higher yield of component crops. In high rainfall year, Broad bed furrow increased soil moisture and productivity of sorghum + pigeon pea and pearl millet + cowpea intercropping system. With respect to total productivity, BBF and CB are always superior that of RD and FB method irrespective of intercropping system and rainfall pattern (Table 9).

Table 8: Water use efficiency of sorghum as influenced by moisture conservation practices

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Water use efficiency (kg ha⁻¹ mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>Control + Surface mulch</td>
<td></td>
</tr>
<tr>
<td>Vertical Mulch (4m)</td>
<td></td>
</tr>
<tr>
<td>Vertical mulch (4m) + surface mulch</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Effect of mulch rate on runoff and soil loss on 10% slope of Oxic paleustaff

4. Land Configuration: Land configuration of the inter bund area can be modified for temporary inter plot harvesting of water and facilitate higher infiltration. These modified configurations could be implemented prior to or after the onset of monsoon and continued till sowing or even adopted after sowing and maintained till harvest.

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### Table 9: Effect of land configuration on growth and yield of sorghum and pigeon pea intercrop

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Root length (cm)</th>
<th>LAI</th>
<th>Straw yield (q ha(^{-1}))</th>
<th>Leaf area</th>
<th>Grain yield (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compartmental bunding (CB)</td>
<td>38.5</td>
<td>3.6</td>
<td>35.2</td>
<td>286</td>
<td>20.7</td>
</tr>
<tr>
<td>Ridging (RD)</td>
<td>36.7</td>
<td>3.00</td>
<td>33.6</td>
<td>263</td>
<td>18.6</td>
</tr>
<tr>
<td>Broad bed furrow (BBF)</td>
<td>37.9</td>
<td>3.21</td>
<td>34.5</td>
<td>277</td>
<td>19.1</td>
</tr>
<tr>
<td>Flat bed (FB)</td>
<td>35.3</td>
<td>2.83</td>
<td>32.2</td>
<td>246</td>
<td>17.8</td>
</tr>
<tr>
<td>LSD(0.05)</td>
<td>1.9</td>
<td>0.35</td>
<td>2.2</td>
<td>14</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Patil (2005)*

**B. Ridge and furrow system:** The system envisages planting of upland rains season crops on 15-20 cm high ridge with 0.5 % slope. Depending on amount and distribution of rainfall, crop yield enhancement ranging 25 to more than 100 % have recorded in case of soybean, maize and sorghum at Jabalpur (Gupta et al.,1979). The system facilitates root zone aeration beside ensuring disposal of runoff at safe velocities (Table 10).

| C. Broad bed and furrow system: | The system involves creation of 90-150 cm wide, 15-20 cm high raised beds with 0.3 to 0.5 % grades. The beds separated by 50 cm wide furrow that drain in to grassed water ways. The system tends to conserve soil, rain water in situ and improves crop yield and sustainability at Indore (Table 10). |

**5. Cropping system:** The crop cover and management factor, C, indicate the influence of cropping system and management of on soil loss forest and grass are the best natural soil protective agencies known and are the about equal in their effectiveness. But both legume and grasses are effectiveness because of their relatively dense cover. The value of C for a specific location is dependent upon a number of factors including the crop, crop growth stage and other management factors. The C value, runoff and soil loss was higher with little soil cover such as bare soil before crop canopy develops and it was lesser where large amount of crop residue or area of dense forest (Table 11).
<table>
<thead>
<tr>
<th>Treatments</th>
<th>Rainfall (mm)</th>
<th>Yield (kg ha(^{-1}))</th>
<th>Soil loss (kg ha(^{-1}))</th>
<th>Nitrogen loss (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>717.3</td>
<td>262</td>
<td>1404</td>
<td>34.88</td>
</tr>
<tr>
<td>BBF (Broad bed and furrow)</td>
<td>717.3</td>
<td>1333</td>
<td>1332</td>
<td>21.38</td>
</tr>
<tr>
<td>BBTF (Broad bed and tied furrow)</td>
<td>717.3</td>
<td>1510</td>
<td>717.1</td>
<td>27.89</td>
</tr>
<tr>
<td>RSB (Raised and sunken beds)</td>
<td>717.3</td>
<td>1546</td>
<td>220.5</td>
<td>7.28</td>
</tr>
</tbody>
</table>

Anonymous, 1994

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Runoff (mm year(^{-1}))</th>
<th>C values</th>
<th>Soil loss (t ha(^{-1}) year(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caster</td>
<td>98</td>
<td>0.61</td>
<td>2.89</td>
</tr>
<tr>
<td>Sorghum</td>
<td>81</td>
<td>0.49</td>
<td>2.31</td>
</tr>
<tr>
<td>Pearl millet</td>
<td>65</td>
<td>0.29</td>
<td>1.38</td>
</tr>
<tr>
<td>Sorghum+ red gram</td>
<td>75</td>
<td>0.47</td>
<td>2.21</td>
</tr>
<tr>
<td>Ajanta grass</td>
<td>42</td>
<td>0.08</td>
<td>0.37</td>
</tr>
<tr>
<td>Cultivated fallow</td>
<td>130</td>
<td>1.00</td>
<td>4.71</td>
</tr>
</tbody>
</table>

Another study was conducted in red soil of Bundelkhand region to evaluate the cropping system on runoff, soil and nutrient losses and Lakaria et al. (2010) reported that highest runoff, soil and nutrient losses were recorded under cultivated fallow whereas cluster bean and sesame are effective for minimizing runoff, soil and nutrients losses and these can ensure production even during poor rainy season with 413.8 mm (Table 12).

<table>
<thead>
<tr>
<th>Canopy cover</th>
<th>Runoff (mm)</th>
<th>Soil loss (kg ha(^{-1}))</th>
<th>OC (kg ha(^{-1}))</th>
<th>N (kg ha(^{-1}))</th>
<th>P (kg ha(^{-1}))</th>
<th>K (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivated fallow</td>
<td>253.0</td>
<td>8.58</td>
<td>72.9</td>
<td>9.7</td>
<td>2.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Maize</td>
<td>172.5</td>
<td>4.69</td>
<td>52.6</td>
<td>5.4</td>
<td>1.9</td>
<td>4.4</td>
</tr>
<tr>
<td>Caster</td>
<td>194.8</td>
<td>5.10</td>
<td>56.6</td>
<td>6.6</td>
<td>2.4</td>
<td>4.8</td>
</tr>
<tr>
<td>Caster + green gram</td>
<td>153.3</td>
<td>3.69</td>
<td>42.2</td>
<td>4.5</td>
<td>1.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Sesame</td>
<td>168.7</td>
<td>4.26</td>
<td>45.8</td>
<td>5.2</td>
<td>2.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Cluster bean</td>
<td>163.0</td>
<td>3.96</td>
<td>44.3</td>
<td>5.0</td>
<td>1.7</td>
<td>3.6</td>
</tr>
<tr>
<td>Groundnut</td>
<td>129.8</td>
<td>3.63</td>
<td>41.2</td>
<td>4.4</td>
<td>1.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Lakaria et al., 2010

6. Intercropping and strip cropping: Intercropping is the one of the important factor to reduce runoff, soil and nutrient losses by soil erosion. Subudhi (2011) result revealed that intercropping of groundnut with pigeon pea planted along contour gave the lowest soil loss (6.27 t ha\(^{-1}\)) and lowest runoff of 230 mm followed by pigeon pea and groundnut planted along the contour. Cultivated fallow gave the highest soil loss (15.75 t ha\(^{-1}\)) and runoff (388.97mm). Thus it can be concluded that intercropping of groundnut with pigeon pea planted along contour may be practiced to reducing the soil loss and runoff in the hilly tribal areas of Kundhamal district of Orissa at 5% land slope. Patil at al. (2004) resulted that among the cropping systems strip cropping was found more effective in controlling runoff and soil loss by 19.18 and 19.61 per cent, respectively total rainfall range was 446.1 to 859.9 mm with an average of 645.1 mm during six year period. The soil moisture content was also improved under strip cropping as compared to intercropping in medium black soil at Solapur in Maharashtra (Table 13).

Table 13: Runoff, soil loss and moisture content as influenced by cropping system (Ave. of 6 yrs)

<table>
<thead>
<tr>
<th>Year</th>
<th>Total</th>
<th>Intercropping</th>
<th>Strip cropping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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7. **Soil Management practices**: Soil management practices such as manual weeding, herbicide spray, mulch application with conventional and conservation tillage affect the soil erosion. Verma et al. (2003) revealed that the conventional tillage (C) + manual weeding produced maximum runoff and soil loss while conventional tillage (C) + straw mulch (SM) recorded minimum runoff and soil loss in both pea and tomato crops. The conservation tillage (CT) was found most effective in reducing the soil sediment losses from 2.08 t ha\(^{-1}\) to 0.35 t ha\(^{-1}\) under pea and 10.55 t ha\(^{-1}\) to 0.72 t ha\(^{-1}\) under tomato crop at Nauni, Solan in Himachal Pradesh in sandy loam soil (Table 14).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Pea (mean of 3 yrs)</th>
<th>Tomato (mean of 2 yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Runoff (mm)</td>
<td>Soil Loss (t ha(^{-1}))</td>
</tr>
<tr>
<td>T1 = Conventional tillage (C)</td>
<td>13.11</td>
<td>1.78</td>
</tr>
<tr>
<td>T2 = C+ MW (Manual weeding)</td>
<td>15.89</td>
<td>2.08</td>
</tr>
<tr>
<td>T3 = C+HA(Herbicide )</td>
<td>14.64</td>
<td>1.93</td>
</tr>
<tr>
<td>T4 = C+SM( Straw mulch)</td>
<td>3.20</td>
<td>0.43</td>
</tr>
<tr>
<td>T5 = C+SM+MW</td>
<td>4.11</td>
<td>0.49</td>
</tr>
<tr>
<td>T6 = C+SM+HA</td>
<td>3.58</td>
<td>0.47</td>
</tr>
<tr>
<td>T7 = Conservation tillage (CT)</td>
<td>4.88</td>
<td>0.35</td>
</tr>
<tr>
<td>T8 = CT+MW</td>
<td>5.92</td>
<td>0.45</td>
</tr>
<tr>
<td>T9 = CT+HA</td>
<td>5.41</td>
<td>0.40</td>
</tr>
<tr>
<td>CD (P=0.05)</td>
<td>0.67</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Summary:**

Soil and water are the most critical basic resources which must be conserved as effectively as possible for sustainable crop production in agriculture. The rainfall, soil type, topography and vegetation are the important factors which affect the soil and water conservation. To conserve soil moisture and water harvesting is important in arid and semi arid regions. The some important technologies and management practices can be useful to conserve soil and water by adopting agronomical, mechanical, engineering and soil management measures namely cropping system, inter and strip cropping, land treatment, contour cultivation, conservation tillage, mulch and residue management, sowing of slope, water harvesting, agro forestry, grasses and other soil management practices in different parts of India.