Climate Change Impact, Adaptation and Mitigation in Agriculture: Methodology for Assessment and Application

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The Indian Agricultural Research Institute (IARI) is the premier national institute of the Indian Council of Agricultural Research for agriculture research, education and extension. Established in 1905, IARI is based in the capital city of New Delhi. The Institute is engaged in climate change research for last 20 years. The focus of IARI's climate change research has been to quantify the sensitivities of current food production systems to different scenarios of climatic change, develop the inventory of greenhouse gas emissions from Indian agriculture, identify options for greenhouse gas mitigation, determine the available management and genetic adaptation strategies for climatic change and climatic variability, develop policy options for implementing mitigation and adaptation strategies and provide policy support for the international negotiations on global climate change.

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FOREWORD

Increased concentration of greenhouse gases (GHGs) in the atmosphere resulted in warming of the global climate system by 0.74 °C between 1906 and 2005. The trends of rise in temperature, heat waves, droughts and floods, and sea level shown by the Indian scientists are in line with the Inter-Governmental Panel on Climate Change (IPCC) though magnitude of changes could differ. The mean temperature in India is projected to increase up to 1.7 ° C in *kharif* (July to October) and upto 3.2 ºC during *rabi* (November to March) season, while the mean rainfall is expected to increase by 10% by 2070. The cases of ravaging and recurrent floods in the north-eastern states during 2002, 2003 and 2004; a record 944 mm of rainfall in a day in Mumbai during 2005 incurring loss of Rs 1000 crore and 1000 lives; devastating floods in Surat, Barmer and Srinagar during the monsoon season of 2006, the droughts in 2000 and 2002, which affected nearly 11 million people in Orissa and the drought of 2006 in north-east which left the people in peril, amply indicate the climatic anomalies. During 2009, the late arrival of monsoon and erratic rainfall later affected rice cultivation in over 5.7 million hectares and 262 districts were declared as drought affected. The western Uttar Pradesh was the worst to be affected with 68 per cent shortage in rainfall. In 2010, when north India received a very good amount of monsoon rain, the eastern part of the country (Bihar, Jharkhand and West Bengal) faced a severe drought. The year 2010 has also been the hottest year ever since the temperature measurement started. The increasing temperature, deficit in rainfall and occurrence of droughts particularly in non-conventional pockets are evidences of weather aberrations indicating climatic risks.

Agriculture, particularly in India with nearly 60% rainfed area, has been a highly risky venture with vagaries of monsoon besides the interplay of other abiotic and biotic factors. Climate change is set to compound the daunting complex challenges already being faced by agriculture. Therefore, concerted efforts are required for mitigation and adaptation to reduce the vulnerability of Indian agriculture to the adverse impacts of climate change and making it more resilient.

However, there are lot of uncertainties about the assessment of impact, adaptation and mitigation of climate change in agriculture. There is a need to develop and apply a standard methodology across the board for various studies related to climate change and agriculture. This book edited by H Pathak, PK Aggarwal and SD Singh of the Division of Environmental Sciences, Indian Agricultural Research Institute is, therefore, very timely and a welcome addition. The book comprehensively presents the recent, internationally accepted, standard methodologies for studying the impacts of climate change on agriculture, measuring and developing inventories of greenhouse gas emission, and analyzing the vulnerabilities and mitigation options. It describes the methodology in a simple and lucid way so that a researcher can adopt it in laboratory and field studies. Individual chapters are dedicated to different subjects. Through inclusion of case studies and presentation of illustrations, effort has been made to make each chapter easy to understand and follow in the laboratory/field studies.

The efforts put by editors as well as authors in compiling and presenting the available information lucidly in this book deserve appreication. I sincerely hope that this book will be very useful for the students and researchers working in the field of global climate change and agriculture.

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PREFACE

Climatic changes and increasing climatic variability are likely to aggravate the problem of future food security by exerting pressure on agriculture. However, there are lot of uncertainties about the assessment of impact, adaptation and mitigation of climate change in agriculture. It is largely because the methodology followed for such assessments is not standardized and sometimes it is inaccurate and imprecise. Researchers follow different methodologies and arrive at contrasting results making it difficult to reach a logical conclusion and develop policy actions. There is a need to develop and apply a standard methodology across the board for various studies related to climate change and agriculture.

This is probably the first book to comprehensively present the recent, internationally accepted, standard methodologies for studying the impacts of climate change on agriculture, measuring and developing inventories of greenhouse gas emission, and analyzing the vulnerabilities and mitigation options. The book describes the methodology in a simple and lucid way so that a researcher can adopt it in laboratory and field studies. Individual chapters are dedicated to subjects such as quantification of climate change impacts on crops in controlled and field conditions, impacts of climate change on water resources, soil fertility, erosion and carbon sequestration, insects, pests, weeds, microbes and diseases; greenhouse gas emission assessment, assessment of regional vulnerability to climate change, selection of crop and vegetable genotypes for climate change adaptation and mitigation, assessing biochemical traits of crops for climate change adaptation and mitigation and assessing the potential of biochar for C sequestration and residue management. With each methodology a case study has been presented illustrating the steps to be followed to achieve the objectives. Efforts have been made to provide example of real case studies. The analysis and application of the results are also illustrated. I compliment the authors of various chapters and editors of this book for their meticulous contributions. I am sure this book will prove an invaluable source reference for the researchers, scientists and students engaged in climate change research.

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We sincerely hope that this book will contribute towards a better understanding of the climate change processes, generating accurate data on greenhouse gas emission and impact of climate change using standard methodologies and develop strategies for mitigation and adaptation in agriculture.

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ABBREVIATIONS

2, 4-D	2, 4-Dichlorophenoxyacetic acid
ABA	Absicis acid
ACC	1-Aminocyclopropane-1-carboxylic acid
AMI	Agronomic management index
APX	Ascorbate peroxidase
ARA	Acetylene reduction assay
BC	Bamboo charcoal
BD	Bulk density
BLASTSIM	Model for simulation of blast disease
BNF	Biological nitrogen fixation
BSA	Bovine serum albumin
BYDV	Barley yellow dwarf virus
CAT	Catalase
CDPKs	Calcium-dependent protein kinases
CEC	Cation exchange capacity
CEE	Carbon equivalent emission
CEF	Controlled-environment facility
CERES-Rice	Crop Growth Model
CF	Continuously flooded
CFC	Chloro fluoro carbon
CH_4	Methane
CLIMEX	Model to predict climate change impact on species
CMS	Cell membrane stability
CO_2	Carbon dioxide
CRI	Crop resistance index
CS	Annual cold stress

CSP	Carbon sequestration potential
CUPRAC	Cupric ion reducing antioxidant capacity
CWPs	Cell wall proteins
DAP	Diammonium phosphate
DAS	Days after sowing
DAT	Days after transplanting
DCD	Dicyandiamide
DHA	Dehydrogenase activity
DP	Drought prone
DS	Annual drought stress
DSR	Direct seeded rice
DST	Department of Science and Technology
DW	Deep water
EC	Eddy covariance
ECD	Electron capture detector
ECI	Efficiency of conversion of ingested food
EF	Emission factor
Eh	Redox potential
EI	Eco-climatic index
ET	Economic threshold
FACE	Free air carbon dioxide enrichment
FAME	Fatty acid methyl esters
FAO	Food and Agriculture Organisation
FAOE	Free air ozone enrichment
FATE	Free air temperature enrichment
FID	Flame ionization detector
FIRBS	Furrow irrigated raised-bed system
FP	Flood prone
FYM	Farmyard manure
GC	Gas chromatograph

GCM	General circulation models
Gg	Giga gram (10^9 g)
GHG	Greenhouse gases
GIS	Geographic information systems
GM	Green manure
GPS	Global positioning systems
GR	Glutathione reductase
Gt	Giga tonne (10^9 tonne)
GWP	Global warming potential
H_2O_2	Hydrogen peroxide
HAT	Hydrogen atom transfer
HEI	Herbicide efficiency index
HI	Harvest index
HPLC	High performance liquid chromatography
HS	Annual heat stress
HSPs	Heat shock proteins
Hz	Hertz
IAEA	International Atomic Energy Agency, Vienna, Austria
IARI	Indian Agricultural Research Institute, New Delhi
ICAR	Indian Council of Agricultural Research, New Delhi
IEF	Isoelectric focussing
IGP	Indo-Gangetic Plains
IPCC	Inter-Governmental Panel on Climate Change
IRGA	Infra-red gas analyzer
IRRI	International Rice Research Institute, Manila
ITEX	International Tundra Experiment
IWM	Integrated Weed Management
IWM	Integrated Water Management
K	Potassium
KI	Potasium iodide

LAI	Leaf area index
LCC	Leaf colour chart
LI	Light interception
Mha	Million hactares
M	Molarity
MA	Multiple aeration
MAC	Methane Asia Campaign
MALDI TOF	Matrix-assisted laser desorption ionisation time of flight
MAPKs	Mitogen-activated protein kinases
MAS	Marker-assisted selection
MBC	Microbial biomass carbon
MBN	Microbial biomass nitrogen
MDA	Malondialdehyde
MIw	Moisture index for week
MSI	Membrane stability index
MT	Million tonnes
N	Nitrogen
N_2O	Nitrous oxide
N_2O-N	N_2O calculated as amount of N
NAR	Net assimilation rate
NATCOM	National Communication to the United Nations Framework Convention on Climate Change
NATP	National Agricultural Technology Project of ICAR
NBT	Nitro-blue tetrazolium
NCU	Neem coated urea
NH_3	Ammonia
NH_4^+-N	NH_4^+ as amount of N
NMR	Nuclear magnatic resonance
NO_3-N	NO_3^- as amount of N
O_3	Ozone
OTC	Open top chambers

P	Phosphorous
PAGE	Polyacrylamide gel electrophoresis
PAL	Phenylalanine ammonia-lyase
PCA	Principal component analysis
PCR	Polymerase chain reaction
PDB	Pee Dee Belemnite
PET	Potential evapotranspiration
Pg	Peta gram (10^{15} gram)
POX	Peroxidase
ppm	Parts per million
ppb	Parts per billion
ppbV	Parts per billion volume
PPO	Polyphenol oxidase
ppt	Parts per trillion
PS	Pecan shell
PVDF	Polyvinylidene fluoride
PVP	Polyvinylpyrrolidone
QTLs	Quantitative trait loci
RAPD	Identified random amplified polymorphic DNA
RCTs	Resource conserving technologies
RGR	Relative growth rate
ROS	Reactive oxygen species
RUBISCO	Ribulosebiphosphate carboxylase
SA	Single aeration
SDS PAGE	Sodium dodecylsulphate polyacrylamide gel electrophoresis
SLA	Specific leaf area
SOC	Soil organic carbon
SOD	Superoxide dismutase
SOM	Soil organic matter
SSWM	Site-specific weed management

SWD	Surface wetness duration
TCA	Trichloroacetic acid
TCD	Thermal conductivity detector
Tg	Tera gram (10^{12} g)
TGT	Temperature gradient tunnel
TIw	Temperature index for week
TPP	Trehalose-6-phosphate phosphatase
TPS	Trehalose-6-phosphate synthase
TYLCV	Tomato leaf curl virus
UDP	Uridinediphosphate
UKCIP	United Kingdom Climate Impact Programs
UNEP	United Nation Environment Programme
UNFCCC	United Nation Framework on Climate Change Convention
USDA	United States Department of Agriculture
USEPA	United States Environment Protection Agency
USG	Urea super granule
UV-radiations	Ultra violet radiations
VPD	Vapour pressure deficit
VPDB	Vienna Pee Dee Belemnite
WCE	Weed control efficiency
WCI	Weed competition index
WCI	Weed control index
WHC	Water holding capacity
WI	Weed index
WPI	Weed persistence index
WS	Annual wet stress
WSE	Weed smothering efficiency
ZT	Zero tillage

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Section I

Climate Change and Agriculture

1

Introduction

H Pathak

Background

For the past some decades, the gaseous composition of earth's atmosphere is undergoing a significant change, largely through increased emissions from energy, industry and agriculture sectors; widespread deforestation as well as fast changes in land use and land management practices. These anthropogenic activities are resulting in an increased emission of radiatively active gases, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), popularly known as the 'greenhouse gases' (GHGs) (Table 1). These GHGs trap the outgoing infrared radiations from the earth's surface and thus raise the temperature of the atmosphere. The global mean annual temperature at the end of the 20th century, as a result of GHG accumulation in the atmosphere, has increased by 0.4–0.7 ºC above that recorded at the end of the 19th century. The past 50 years have shown an increasing trend in temperature @ 0.13 °C/decade, while the rise in temperature during the past one and half decades has been much higher

Table 1. Abundance and lifetime of greenhouse gases in the atmosphere

Parameters	CO_2	CH_4	N_2O	Chlorofluorocarbons
Average concentration 100 years ago (ppbV)	290,000	900	270	0
Current concentration (ppbV) (2007)	380,000	1,774	319	3-5
Projected concentration in the year 2030 (ppbV)	400,000-500,000	2,800-3,000	400-500	3-6
Atmospheric lifetime (year)	5-200	9-15	114	75
Global warming potential (100 years relative to CO_2)	1	25	298	4750-10900

Source: IPCC (2007)

(Figure 1). The Inter-Governmental Panel on Climate Change has projected the temperature increase to be between 1.1 °C and 6.4 °C by the end of the 21st Century (IPCC, 2007). The global warming is expected to lead to other regional and global changes in the climate-related parameters such as rainfall, soil moisture, and sea level. Snow cover is also reported to be gradually decreasing. Therefore, concerted efforts are required for mitigation and adaptation to reduce the vulnerability of agriculture to the adverse impacts of climate change and making it more resilient (Figure 2).

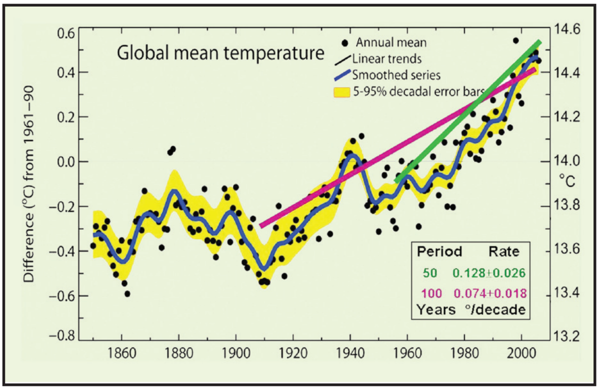

Figure 1. Trends in global temperature over the years (IPCC, 2007)

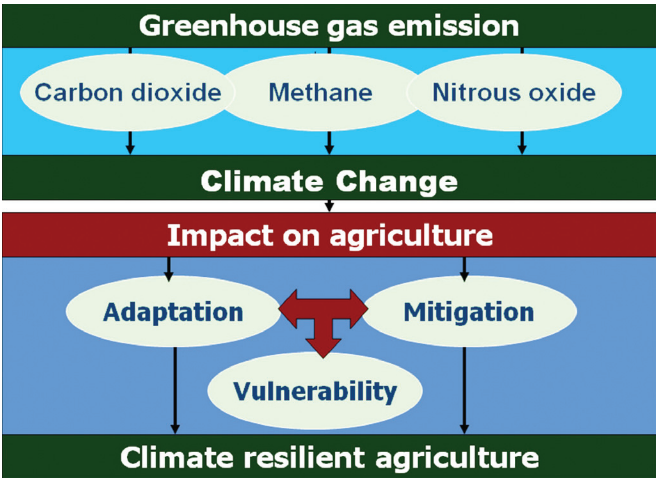

Figure 2. Framework of climate change impact, mitigation and adaptation in agriculture

The adaptive capacity of poor farmers is limited because of subsistence agriculture and low level of formal education. Therefore, simple, economically viable and culturally acceptable adaptation strategies have to be developed and implemented. Furthermore, the transfer of knowledge as well as access to social, economic, institutional, and technical resources need to be provided and integrated within the existing resources of farmers. This chapter provides an outline about the impacts of climate change on Indian agriculture and the potential strategies for their mitigation and adaptation.

Emission of Greenhouse Gases

The three major GHGs are carbon dioxide, methane and nitrous oxide, besides chlorofluorocarbons. A brief description about their sources and sinks is given below.

Carbon Dioxide

The main sources of carbon dioxide emission are decay of organic matter, forest fires, eruption of volcanoes, burning of fossil fuels, deforestation and land-use changes. Agriculture is also a contributor to CO_2 emission but is not considered a major source of this important GHG. Within agriculture, soil is the main contributor with factors such as soil texture, temperature, moisture, pH, and available C and N, influencing CO_2 emission from soil. Emission of CO_2 is more from a tilled soil than from an undisturbed soil (no till). Temperature has a marked effect on CO_2 evolution from soil by influencing root and soil respiration. It may be mentioned that plants, oceans and atmospheric reactions are the major sinks of carbon dioxide.

Methane

Methane is about 25-times more effective as a heat-trapping gas than CO_2. The main sources of methane are: wetlands, organic decay, termites, natural gas and oil extraction, biomass burning, rice cultivation, cattle and refuse landfills. The primary sources of methane from agriculture include animal digestive processes, rice cultivation and manure storage and handling. The removal in the Stratosphere and soil are the main sinks of methane.

In ruminant animals, methane is produced as a by-product of the digestion of feed in the rumen under anaerobic condition. Methane emission is related to the composition of animal diet (grass, legume, grain and concentrates) and the proportion of different feeds (e.g., soluble residue, hemicellulose and cellulose content). Mitigation of methane emitted from livestock is approached most effectively by strategies that reduce feed input per unit of product output. Nutritional, genetic and management strategies to improve feed efficiency increase the rate of product (milk, meat) output per animal. Because most CH_4 is produced in the rumen by fermentation, practices that speed the passage of feed from the rumen can also reduce methane formation.

Methane is also formed in soil through the metabolic activities of a small but highly specific bacterial group called 'methanogens'. Their activity increases in the submerged, anaerobic conditions developed in the wetland rice fields, which limit the transport of oxygen into the soil, and the microbial activities render the water-saturated soil practically devoid of oxygen. The upland, aerobic soil does not produce methane. Water management, therefore, plays a major role in methane emission from soil. Altering water management practices, particularly mid-season aeration by short-term drainage as well as alternate wetting and drying can greatly reduce methane emission from rice cultivation. Improving organic matter management by promoting aerobic degradation through composting or incorporating into soil during off-season drain-period is another promising technique.

Nitrous Oxide

As a greenhouse gas, nitrous oxide is 298-times more effective than CO_2. Forests, grasslands, oceans, soils, nitrogenous fertilizers, and burning of biomass and fossil fuels are the major sources of nitrous oxide, while it is removed by oxidation in the Stratosphere. Soil contributes to the largest amount of nitrous oxide emission. The major sources are soil cultivation, fertilizer and manure application, and burning of organic material and fossil fuels. From an agricultural perspective, nitrous oxide emission from soil represents a loss of soil nitrogen, reducing the nitrogen-use efficiency. Appropriate crop-management practices, which lead to increased N-use efficiency, hold the key to reduce nitrous oxide emission. Site-specific nutrient management, fertilizer placement and proper type of fertilizer supply nutrients in a better accordance with plant demands, thereby reduce nitrous oxide emission.

Impacts of Climate Change on Agriculture

Global climatic changes can affect agriculture through their direct and indirect effects on the crops, soils, livestock and pests (Table 2). An increase in atmospheric carbon dioxide level will have a fertilization effect on crops with C3 photosynthetic pathway and thus will promote their growth and productivity. The increase in temperature, depending upon the current ambient temperature, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, affect the survival and distribution of pest populations, hasten nutrient mineralization in soils, decrease fertilizer-use efficiencies, and increase evapo-transpiration rate. Indirectly, there may be considerable effects on land

Table 2. Potential impacts of climate change on different sectors of agriculture

Sector	Impact
Crop	• Increase in ambient CO_2 concentration is beneficial since it leads to increased photosynthesis in several crops, especially those with C3 mechanism of photosynthesis such as wheat and rice, and decreased evaporative losses. Despite this, yields of major cereals crops, especially wheat are likely to be reduced due to decrease in grain filling duration, increased respiration, and / or reduction in rainfall/irrigation supplies. • Increase in extreme weather events such as floods, droughts, cyclones and heat waves will adversely affect agricultural productivity. • Reduction in yields in the rainfed areas due to changes in rainfall pattern during monsoon season and increased crop water demand. • Incidence of cold waves and frost events may decrease in future due to global warming and it would lead to a decreased probability of yield loss associated with frost damage in northern India in crops such as mustard and vegetables. • Quality of fruits, vegetables, tea, coffee, aromatic, and medicinal plants may be affected. • Incidence of pest and diseases of crops to be altered because of more enhanced pathogen and vector development, rapid pathogen transmission and increased host susceptibility. • Agricultural biodiversity is also threatened due to the decrease in rainfall and increase in temperature, sea level rise, and increased frequency and severity of droughts, cyclones and floods.
Water	• Demand for irrigation water would increase with rise in temperature and evapo-transpiration rate. It may result in lowering of groundwater table at some places. contd...

Table 2 contd....

Sector	Impact
	• The melting of glaciers in the Himalayas will increase water availability in the Ganges, Bhramaputra and their tributaries in the short-run, but in the long-run, the availability of water will decrease considerably. • A significant increase in runoff is projected in the wet season that, however, may not be very beneficial unless storage infrastructure is vastly expanded. This additional water in the wet season, on the other hand, may lead to increase in frequency and duration of floods. • The water balance in different parts of India will be disturbed and the quality of groundwater along the coastal track will be affected more due to intrusion of sea waters.
Soil	• Organic matter content, which is already quite low in Indian soils, would become still lower. Quality of soil organic matter may be affected. • The residues of crops under the elevated CO_2 concentrations will have higher C:N ratio, and this may reduce their rate of decomposition and nutrient supply. • Rise in soil temperature will increase N mineralization, but its availability may decrease due to increased gaseous losses through processes such as volatilization and denitrification. • There may be a change in rainfall volume and frequency, and wind may alter the severity, frequency and extent of soil erosion. • Rise in sea level may lead to salt-water ingression in the coastal lands, turning them less suitable for conventional agriculture.
Livestock	• Climate change will affect fodder production and nutritional security of livestock. Increased temperature would enhance lignification of plant tissues, reducing the digestibility. Increased water scarcity would also decrease production of feed and fodder. • Major impacts on vector-borne diseases will be through expansion of vector populations in the cooler areas. Changes in rainfall pattern may also influence expansion of vectors during wetter years, leading to large outbreaks of diseases. • Global warming would increase water, shelter, and energy requirement of livestock for meeting the projected milk demands. • Climate change is likely to aggravate the heat stress in dairy animals, adversely affecting their reproductive performance.
Fishery	• Increasing temperature of sea and river water is likely to affect breeding, migration and harvests of fishes. • Impacts of increased temperature and tropical cyclonic activity would affect the capture, production and marketing costs of the marine fish. • Coral bleaching is likely to increase due to higher sea surface temperature.

Source: Aggarwal *et al*. (2009a)

use due to snow melt, availability of irrigation water, frequency and intensity of inter- and intra-seasonal droughts and floods, soil organic matter transformations, soil erosion, changes in pest profiles, decline in arable areas due to submergence of coastal lands, and availability of energy. Equally important determinants of food supply are socio-economic environment, including government policies, capital availability, prices and returns, infrastructure, land reforms, and inter- and intra-national trade that might be affected by the climatic change.

Reduction in Crop Yield

Rise in the mean temperature above a threshold level will cause a reduction in agricultural yields. A change in the minimum temperature is more crucial than a change in the maximum temperature. Grain yield of rice, for example, declined by 10% for each 1 °C increase in the growing season minimum temperature above 32 °C (Pathak *et al*., 2003). The climate change impact on the productivity of rice in Punjab (India) has shown that with all other climatic variables remaining constant, temperature increases of 1 °C, 2 °C and 3 °C, would reduce the grain yield of rice by 5.4%, 7.4% and 25.1%, respectively (Aggarwal *et al*., 2009b).

Shortage of Water

The increased temperature would result in more water shortages and the demand for irrigation water would rise. Increase in air temperature will lead to more potential evapotranspiration in the areas south of 40° N. Likewise, water shortage due to climate change would result in about 20% net decline in the rice yields in India.

Irregularities in Onset of Monsoon, Drought, Flood and Cyclone

Indian agriculture is highly dependent on the onset, retreat and magnitude of monsoon precipitation, particularly in the rainfed areas of east, north-east and south India. Climate modelers and IPCC documents have projected possibilities of increasing variability in Asian Monsoon circulation in a warmer world. Despite expansion of area under irrigation, droughts, caused by inadequate and uneven distribution of rainfall, continue to be the most important climatic aberrations, which influence the agricultural production in India. The severity of a drought will be intensified in a warmer world. Intense and frequent floodings due to climate change would be a major problem in the Indian subcontinent.

Rise in Sea Level

In South, South East and East Asia about 10% of the regional rice production, which is enough to feed 200 million people, is from the areas that are susceptible to 1 m rise in the sea level. Direct loss of land combined with less favourable hydraulic conditions may reduce rice yields by 4% if no adaptation measures are taken, endangering the food security of at least of 75 million people. Saltwater intrusion and soil salinization are other concerns for agricultural productivity.

Decline in Soil Fertility

Soil temperature affects the rates of organic matter decomposition and release of nutrients. At high temperatures, though nutrient availability will increase in the short-term, in the long-run organic matter content will diminish, resulting in a decline in soil fertility.

Loss of Biodiversity

Species of animals and plants are estimated to disappear at a rate which would be about 100-times faster than the historical record, largely as a result of human activities. A detailed assessment of the 394 species of primates from South America to Indonesia has indicated that 29% are in danger of disappearing due to hunting, habitat loss and climate change.

Pests, Weeds and Diseases

As temperature increases, the insect-pests will become more abundant through a number of inter-related processes, including range extensions and phenological changes, as well as increased rates of population development, growth, migration and over-wintering. The climate change is likely to alter the balance between insect pests, their natural enemies and their hosts. The rise in temperature will favour insect development and winter survival. Rising atmospheric carbon dioxide concentrations may lead to a decline in food quality for plant-feeding insects, as a result of reduced foliar nitrogen levels. The epidemiology of plant diseases will be altered. The prediction of disease outbreaks will be more difficult in periods of rapidly changing climate and unstable weather. Environmental instability and increased incidence of extreme weather may reduce the effectiveness of pesticides on targeted pests or result in more injury to non-target organisms.

Mitigation Strategies to Climate Change

The strategies for mitigating methane emission from rice cultivation could be alteration in water management, particularly promoting mid-season aeration by short-term drainage; improving organic matter management by promoting aerobic degradation through composting or incorporating it into soil during off-season drained period; use of rice cultivars with few unproductive tillers, high root oxidative activity and high harvest index; and application of fermented manures like biogas slurry in place of unfermented farmyard manure (Pathak and Wassmann, 2007). Methane emission from ruminants can be reduced by altering the feed composition, either to reduce the percentage which is converted into methane or to improve the milk and meat yield.

The most efficient management practice to reduce nitrous oxide emission is site-specific, efficient nutrient management (Pathak, 2010). The emission could also be reduced by nitrification inhibitors such as nitrapyrin and dicyandiamide (DCD). There are some plant-derived organics such as neem oil, neem cake and karanja seed extract which can also act as nitrification inhibitors.

Mitigation of CO_2 emission from agriculture can be achieved by increasing carbon sequestration in soil through manipulation of soil moisture and temperature, setting aside surplus agricultural land, and restoration of soil carbon on degraded lands. Soil management practices such as reduced tillage, manuring, residue incorporation, improving soil biodiversity, micro aggregation, and mulching can play important roles in sequestering carbon in soil. Some technologies such as intermittent drying, site-specific N management, etc. can be easily adopted by the farmers without additional investment, whereas other technologies need economic incentives and policy support (Wassmann and Pathak, 2007).

Adaptation Strategies to Climate Change

To deal with the impact of climate change, the potential adaptation strategies are: developing cultivars tolerant to heat and salinity stress and resistant to flood and drought, modifying crop management practices, improving water management, adopting new farm techniques such as resource conserving technologies (RCTs), crop diversification, improving pest management, better weather forecasting and crop insurance and harnessing the indigenous technical knowledge of farmers. Some of these strategies are discussed below.

Developing Climate-ready Crops

Development of new crop varieties with higher yield potential and resistance to multiple stresses (drought, flood, salinity) will be the key to maintain yield stability. Improvement in germplasm of important crops for heat-stress tolerance should be one of the targets of breeding programme. Similarly, it is essential to develop tolerance to multiple abiotic stresses as they occur in nature. The abiotic stress tolerance mechanisms are quantitative traits in plants. Germplasm with greater oxidative stress tolerance may be exploited as oxidative stress tolerance is one example where plant's defence mechanism targets several abiotic stresses. Similar to the research efforts on conversion of rice from C3 to C4 crop, steps should be taken for improvement in radiation-use efficiency of other crops as well.

Improvement in water-use and nitrogen-use efficiencies is being attempted since long. These efforts assume more relevance in the climate change scenarios as water resources for agriculture are likely to dwindle in future. Nitrogen-use efficiency may be reduced under the climate change scenarios because of high temperatures and heavy precipitation events causing volatilization and leaching losses. Apart from this, for exploiting the beneficial effects of elevated CO_2 concentrations, crop demand for nitrogen is likely to increase. Thus, it is important to improve the root efficiency for mining the water and absorption of nutrients. Exploitation of genetic engineering for 'gene pyramiding' has become essential to pool all the desirable traits in one plant to get the 'ideal plant type' which may also be 'adverse climate-tolerant' genotype.

Farmers need to be provided with cultivars with a broad genetic base. Their adaptation process could be strengthened with availability of new varieties having tolerance to drought, heat and salinity and thus, minimize the risks of climatic aberrations. Similarly, development of varieties is required to offset the emerging problems of shortening of growing season and other vagaries of production environment. Farmers could better stabilize their production system with basket of technological options.

Crop Diversification

Diversification of crop and livestock varieties, including replacement of plant types, cultivars, hybrids, and animal breeds with new varieties intended for higher drought or heat tolerance, are being advocated as having the potential to increase productivity in the face of temperature and moisture stresses. Diversity in the seed genetic structure and composition has been recognized as an effective defence against disease and pest outbreak and climatic hazards. Moreover, demand for high-value food commodities, such as fruits, vegetables, dairy, meat, eggs and fish is increasing because of growing income and urbanization. This is reducing the demand for traditional rice and wheat. Diversification from rice-wheat towards high-value commodities will increase income and result in reduced water and fertilizer use. However, there is a need to quantify the impacts of crop diversification on income, employment, soil health, water use and greenhouse gas emissions. A significant limitation of diversification is that it is costly in terms of the income opportunities that farmers forego, i.e., switching of crop can be expensive, making crop diversification typically less profitable than specialization. Moreover, traditions can often be difficult to overcome and will dictate local practices.

Changes in Land-use Management Practices

Changing land-use practices such as the location of crop and livestock production, rotating or shifting production between crops and livestock, shifting production away from marginal areas, altering the intensity of fertilizer and pesticide application as well as capital and labour inputs can help reduce risks from climate change in farm production. Adjusting the cropping sequence, including changing the timing of sowing, planting, spraying, and harvesting, to take advantage of the changing duration of growing seasons and associated heat and moisture levels is another option. Altering the time at which fields are sowed or planted can also help farmers regulate the length of the growing season to better suit the changed environment. Farmer adaptation can also involve changing the timing of irrigation or use of other inputs such as fertilizers.

Adjusting Cropping Season

Adjustment of planting dates to minimize the effect of temperature increase-induced spikelet sterility can be used to reduce yield instability, by avoiding having the flowering period to coincide with the hottest period. Adaptation measures to reduce the negative effects of increased climatic variability as normally experienced in arid and semi-arid tropics may include changing of the cropping calendar to take advantage of the wet period and to avoid extreme weather events (e.g., typhoons and storms) during the growing season. Cropping systems may have to be changed to include growing of suitable cultivars (to counteract compression of crop development), increasing crop intensities (i.e., the number of successive crop produced per unit area per year) or planting different types of crops. Farmers will have to adapt to changing hydrological regimes by changing crops.

Efficient Use of Resources

The resource-conserving technologies (RCTs) encompass practices that enhance resource- or input-use efficiency and provide immediate, identifiable and demonstrable economic benefits such as reduction in production costs; savings in water, fuel and labour requirements; and timely establishment of crops, resulting in improved yields. Yields of wheat in heat- and water-stressed environments can be raised significantly by adopting RCTs, which minimize unfavourable environmental impacts, especially in small and medium-scale farms. Resource conserving practices like zero-tillage (ZT) can allow farmers to sow wheat sooner after rice harvest, so the crop heads and fills the grain before the onset of pre-monsoon hot weather. As the average temperatures in the region rise, early sowing will become even more important for wheat. Field results have shown that the RCTs are increasingly being adopted by farmers in the rice-wheat belt of the Indo-Gangetic Plains because of several advantages of labour saving, water saving, and early planting of wheat. The RCTs in rice-wheat system also have pronounced effects on mitigation of greenhouse gas emission and adaptation to climate change (Pathak *et al*. 2009). These approaches of crop management should be coupled with the measures of crop improvement for wider adaptation to climate change.

Soil and water management is highly critical for adaptation to climate change. With higher temperatures and changing precipitation patterns, water will further become a scarce resource. Serious attempts towards water conservation, water harvesting improvement in irrigation accessibility, and water-use efficiency will become essential for crop production and livelihood management. Farmers have to be trained and motivated for adopting on-farm water conservation techniques, micro-irrigation systems for better water-use efficiency, selection of appropriate crops, etc. Principles of increasing water infiltration with improvement in soil aggregation, decreasing runoff with use of contours, ridges, vegetative hedges, etc. and reducing soil evaporation with use of crop residues mulch could be employed for better management of soil-water.

Relocation of Crops in Alternative Areas

Climate change in terms of increased temperature, CO_2 level, droughts and floods would affect production of crops. But, the impact will be different across crops and regions. There is a need to identify the crops and regions that are more sensitive to climate changes/variability and relocate them in more suitable areas. For example, it is apprehended that increased temperature would affect the quality of crops, particularly important aromatic crops such as basmati rice and tea. Alternative areas that would become suitable for such crops from quality point of view need to be identified and assessed for their suitability.

Harnessing Indigenous Technical Knowledge of Farmers

Farmers in South Asia, often poor and marginal, are experimenting with the climatic variability for centuries. There is a wealth of knowledge on the range of measures that can help in developing technologies to overcome climate vulnerabilities. There is a need to harness that knowledge and fine-tune them to suit the modern needs. Traditional ecological knowledge of people developed and carried which have stood the test of time could provide insights and viable options for adaptive measures. Anthropological and sociological studies have highlighted the importance of community based resource management and social learning to enhance their capacity to adapt to the impacts of future climate change. Tribal and hill knowledge systems are pregnant with potential indigenous practices used for absorption and conservation of rainwater, nutrient and weed management, crop production and plant protection. Their belief systems have effectively helped in weather forecasting and risk adjustment in crop cultivation. During the course of their habitation, the indigenous people of Himalayan terrain region through experience, experimentation and accumulated knowledge, have devised ways of reducing their vulnerability to natural hazards. Studies have shown that their understanding was fairly evolved in the matters of earthquake, landslide and drought and they have devised efficient ways of mitigating the effect of natural or climatic changes.

Improved Pest Management

Changes in temperature and variability in rainfall would affect incidence of pests and disease and virulence of major crops. It is because climate change will potentially affect the pest/weed-host relationship by affecting the pest/

weed population, the host population and the pest/weed-host interactions. Some of the potential adaptation strategies could be: (i) developing cultivars resistance to pests and diseases; (ii) adoption of integrated pest management with more emphasis on biological control and changes in cultural practices, (iii) pest forecasting using recent tools such as simulation modelling, and (iv) developing alternative production techniques and crops, as well as locations, that are resistant to infestations and other risks. Management of pests and diseases with use of resistant varieties and breeds; alternative natural pesticides; bacterial and viral pesticides; pheromones for disrupting pest reproduction, etc. could be adopted for sustainability of agricultural production process. Bio-agents have a crucial role in pest management, hence practices to promote natural enemies like release of predators and parasites; improving the habitat for natural enemies; facilitating beetle banks and flowering strips; crop rotation and multiple cropping should be integrated in pest management practices. Reduction in use of pesticides will also help in reducing carbon emissions.

Better Weather Forecasting and Crop Insurance Schemes

Weather forecasting and early warning systems will be very useful in minimizing risks of climatic adversaries. Information and communication technologies (ICT) could greatly help the researchers and administrators in developing contingency plans. Effective crop insurance schemes should be evolved to help the farmers in reducing the risk of crop failure due to these events. Both formal and informal, as well as private and public, insurance programs need to be put in place to help reduce income losses as a result of climate-related impacts. However, information is needed to frame out policies that encourage effective insurance opportunities.

Micro-finance has been a success among rural poor, including women. Low-cost access to financial services could be a boon for vulnerable farmers. Growing network of mobile telephony could further speed up SMS-based banking services and help the farmers in having better integration with financial institutions. However, compared to micro-finance, micro-insurance innovations and availability is limited. There is a need to develop sustainable insurance system, while the rural poor are to be educated about availing such opportunities.

Conclusions

Climatic changes and increasing climatic variability are likely to aggravate the problems of future food security by exerting pressure on agriculture. However, there are lot of uncertainties about the assessment of impact, adaptation and mitigation of climate change in agriculture. It is mainly because the methodology followed for such assessments is not standardized and sometimes is inaccurate and imprecise. Researchers follow different methodologies and arrive at contrasting results making it still more difficult to reach a logical conclusion and develop policy actions. There is a need to develop and apply a standard methodology across the board for various studies related to climate change and agriculture. The different chapters of this book present the recent, internationally accepted, and standard methodologies for studying the impacts of climate change on agriculture, measuring and developing inventories of greenhouse gas emissions, analyzing the vulnerabilities and application of adaptation and mitigation options.

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Section II

Measurement of Greenhouse Gas Emission from Agriculture

2

Greenhouse Gas Emission from Agriculture

H Pathak, A Bhatia and N Jain

Introduction

The sunlight enters a greenhouse through the transparent glass or plastic and heats the plants but the heat emitted by the plants in the form of infrared radiations cannot pass through the glass or plastic roof and walls of the greenhouse. As a result, temperature inside the greenhouse rises. The phenomenon is known as 'greenhouse effect'. In a similar manner, the earth's atmosphere, which acts like the glass or plastic roof and walls of a greenhouse, allows most of incoming sunlight to pass through and heat the surface. But the heat radiated by the heated surface cannot pass freely into the space because of the presence of a number of gases such as carbon dioxide, methane, ozone, nitrous oxide and water vapour in the atmosphere. Consequently, the average temperature of earth's atmosphere is increasing — a phenomenon which is commonly known as global warming. It has been found that carbon dioxide contributes 60%, methane 15% and nitrous oxide 5% to the global warming (IPCC, 2007). Also, as a heat-trapping gas, methane is 25-times and nitrous oxide is 298-times more effective than carbon dioxide (Table 1). Wetlands, organic matter decay, cattle and refuse landfills, termites and natural gas and oil extraction are the main sources of methane, whereas escape into the stratosphere and adsorption by soil are the main sinks. The primary sources of methane emission in agriculture include rice cultivation, biomass burning, animal digestive processes and manure storage and handling. Forests, grasslands, oceans, soils, nitrogenous fertilizers, burning of biomass and fossil fuels are the sources of nitrous oxide, while it is removed by oxidation in the stratosphere. Soil with a contribution of about 65% is the major contributor to the total nitrous oxide emission. The main processes that cause emission of nitrous oxide are soil cultivation, fertilizer and manure application, and burning of organic materials and fossil fuels. The main sources of carbon dioxide are decay of organic matter, forest fires, eruption of volcanoes, burning of fossil fuels, deforestation and land-use change, whereas plants, oceans and atmospheric reactions are the major sinks. Though agricultural soil is a

Table 1. Atmospheric concentration, lifetime and global warming potential (GWP) of major greenhouse gases

Greenhouse gas	Atmospheric concentration	Lifetime (years)	GWP (100 years)
Carbon dioxide	387 ppm	Variable	1
Methane	1780 ppb	12	25
Nitrous oxide	319 ppb	114	298
CFC 11	250 ppt	45	4600
CFC 12	533 ppt	100	10600
HCFC 22	132 ppt	11.9	1700
HFC 23	12 ppt	260	12000

Source: IPCC (2007)

small contributor of carbon dioxide, factors such as soil texture, temperature, moisture, pH, available C and N contents influence CO_2 emission from soil.

Measurement of Methane and Nitrous Oxide Emission

Methods used for the measurement of greenhouse gases (GHGs) vary with respect to gas to be measured, spatial coverage, temporal resolution, cost, precision and accuracy of the method. The measured values, however, can only be interpreted accurately if factors related to soil, plant and climate, which determine the production, consumption and emission of the greenhouse gases, are taken into account. Among these, soil texture, pH, organic matter content, moisture content, nitrate and ammonium content, redox potential, plant cover, and climatic factors such as air temperature, incoming radiation, relative humidity and precipitation are important. Soil physical factors such as bulk density, porosity and pore size distribution are also important in determining the storage and movement of gases in the soil.

Two methods generally used to measure methane and nitrous oxide emissions from soils are:

(i) Soil Chamber Method, and
(ii) Micrometeorology

- *Soil Chamber Method* — In this method, gas emissions from soil are estimated by measuring the short-term buildup of the gas in a sealed enclosure placed over the soil surface. This restricts the volume of air exchange across the covered surface. Any net emission or uptake from soil can be measured as a change in the concentration of the gas. The soil closed-chamber method is the widely used and is relatively less expensive method to estimate emissions of GHGs from soil.
- *Micrometeorology* — In this method, vertical concentration gradients of the gas measured using eddies correlation. It is useful for evaluating regional model simulations (scaling from site to region). However, requirement of expensive equipments and cumbersome sampling and measurement procedures restrict its use for estimation of methane and nitrous oxide. The details of this method are described in Chapter 3.

Closed Chamber Method

Using closed chambers the gas flux from a soil can be determined by collecting gas samples periodically from the chambers and measuring the change in concentration of a gas with time during the period of linear concentration change (Hutchison and Mosier 1981). Chambers can be made from a material like rigid plastic, metal or acrylic sheet. For collecting gas samples from crop fields, generally, chambers with dimensions of 50 cm × 30 cm × 100 cm (Figure 1) made of 6-mm

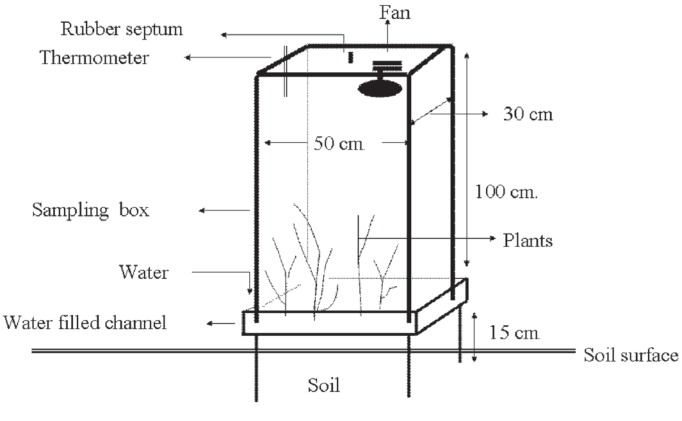

Figure 1. Closed-chamber used for collection of methane and nitrous oxide samples from a field

acrylic sheets are used. Aluminum channels, used with each chamber, are inserted 10-cm into the soil and the channels are filled with water to make the system air-tight. A battery-operated fan is fixed inside the chamber to homogenize the inside air. A thermometer is also inserted to record the inside temperature.

To measure a gas flux, the chamber is fixed on the top of the pre-inserted aluminum channels. The change in concentration of methane or nitrous oxide with time is determined by taking gas samples from the chamber headspace with the help of a syringe. The plastic or preferably greased glass medical syringes of 20-50 mL capacity and fitted with a 2-way or 3-way stop cock are generally used. Gas samples are collected from the headspace immediately after sealing and at equal time intervals thereafter over a period not exceeding 2 hours. Gas samples are drawn with the help of a hypodermic needle (24 gauges). After drawing the sample, syringes are made air-tight with a three-way stopcock. A minimum of three measurements should be made to check linearity in increase in concentration of a gas. A deviation from a straight line indicates either an inadequately sealed chamber or a decrease in the gas concentration gradient between the zone of production in the soil and the chamber atmosphere changes the gas diffusion rate with time. The gas samples are analyzed using a gas chromatograph (GC). The chamber cover should be removed after the final sample to minimize the disturbance to environmental conditions within the enclosure formed by the chamber walls. Samples of four replications of each treatment are taken from the fields and the average is taken as the representative value for the treatment. Head space volume and temperature inside the chamber are also recorded, which are used to calculate the flux of gas.

To transport gas samples over long distances to the analytical laboratory, evacuated vials fitted with rubber/silicon septa (e.g. vacutainers/exetainers) may be used. The septa of the vials should be cleaned with a detergent and the vials be evacuated using a vacuum pump before use. An alternative method is the use of glass serum bottles fitted with butyl rubber stoppers. The vials are taken to the sampling site, and filled with the gas sample with a syringe. By injecting sufficient volume of gas sample to achieve over-pressure, e.g. 10 mL into a 9-mL vial, contamination problems can be prevented.

The methodology has been described step-wise in the following sections.

Collection of Gas Samples

- Gas sample is collected using closed-chamber technique (Figure 1).
- Chambers of 50 cm × 30 cm × 100 cm size (according to experiment) made of 5 to 6-mm acrylic sheets are required for sampling.
- An aluminum channel is placed in the field and is used with each acrylic chamber.
- The aluminum channels should be inserted 10 cm inside the soil and the channels are filled with water to make the system air-tight.
- One 3-way stopcock (Eastern Medikit Ltd. India) is fitted at the top of chamber to collect gas samples.
- The chamber should be thoroughly flushed several times with a 50-mL syringe to homogenize the inside air thoroughly.
- Gas samples are to be drawn with the help of a 20-50 mL syringe using a hypodermic needle (24 gauges).
- After drawing samples, the chamber should be made air tight with the help of a stop cock.
- Head space volume inside the box should be recorded, which will be used to calculate flux of gas (nitrous oxide or methane).
- Gas samples are collected at 0 hour, ½ hour and 1 hour after the chamber has been placed over the aluminium channel.

Estimation of Greenhouse Gases

Methane

In gas samples, the concentration of methane is estimated using a Gas Chromatograph fitted with a flame ionization detector (FID). The FID detects the substances that produce ions when heated in H_2-air flame. The detector, however, is insensitive to permanent gases, water and inorganic ions, which do not ionize at 2100 °C. The sample along with the carrier gas (eluent) enters the hydrogen jet via a millipore filter. The sample components get ionized to form ions and free electrons on entering the flame at the tip of the jet. The electrons so produced are drawn towards a collector. Due to this movement of electrons, there is a flow of current. The flow of current across an external resistor, sensed as voltage drop, is amplified and displayed on the recorder. The entire assembly is housed in an oven to prevent condensation of water vapour formed as a result of combustion.

Gas samples containing methane are introduced into the gas chromatograph through a sampling valve with the help of a syringe fitted with a two-way nylon stopcock. A gas sample loop of 1 or 2 cm^3 is fitted to the sample valve. Although, it is possible to inject the sample manually, use of a sample loop should be preferred. The configuration of the valve may be designed as per the needs of user. Methane analysis can be accomplished by various modifications of GC settings and column materials. Each individual setting will have to be optimized empirically in order to achieve a satisfactory separation and detection.

Methane can be separated from other gaseous components on a Porapak N or Porapak Q column (3-m-long stainless steel or nickel with 3.175-mm outside diameter) maintained at 50 °C having a carrier gas flow (helium, nitrogen or argon) of 20-30 cm^3 min^{-1}. An alternative is the use of a molecular sieve (13 × 60-80 mesh size) as a column material and synthetic air as carrier gas. Methane is detected with the help of a FID maintained at 250 °C. Column temperature is maintained at 70 °C. H_2 with a flow rate of 30-40 mL min^{-1} is used for FID. The sampling valve can be accentuated manually or time-controlled pneumatically or electronically using a computer or GC-contained microprocessor. A GC-computer interface is used to plot and measure the peak area. The methane standards (1 ppm, 5 ppm and 10 ppm) are used as a primary standard.

Calculation of Methane Flux

Cross-sectional area of the chamber (m^2) = A
Headspace (m) = H
Volume of headspace (L) = 1000 × AH
CH_4 concentration at 0 time ($\mu L\ L^{-1}$) = C_o
CH_4 concentration after time t ($\mu L\ L^{-1}$) = C_t
Change in concentration in time t ($\mu L\ L^{-1}$) = $(C_t - C_o)$
Volume of CH_4 evolved in time t (μL) = $(C_t - C_o) \times 1000\ AH$
When t is in hours, then flux ($mL\ m^{-2}\ h^{-1}$) = $[(C_t\text{-}C_o) \times AH)/(A \times t)$
Now 22.4 mL of CH_4 is 16 mg at STP
Hence, Flux = $[(C_t - C_o)/t] \times H \times 16/22.4 \times 10000 \times 24$ mg ha^{-1} d^{-1}

Nitrous Oxide

In gas samples, the concentration of nitrous oxide is estimated with the help of a Gas Chromatograph fitted with an electron capture detector (ECD) and

$6' \times {}^{1}/_{8}''$ stainless steel column (Porapak N). The ECD is used for the detection of those substances which have affinity for electrons. The detector consists of two electrodes, one of which is treated with radioactive ^{63}Ni, which emits beta rays. These high-energy electrons bombard the carrier gas (N_2 or argon mixture) to produce a large number of low-energy (or thermal) secondary electrons. The other positively polarized electrode collects these electrons. This steady state current is reduced when an electrophilic sample component passing through the gap between the two electrodes captures some of these electrons, thus providing an electrical reproduction of the GC peak. This detector can also contain besides ^{63}Ni some other radioactive elements like tritium or scandium. Although the sensitivity of ^{63}Ni is lower, it remains constant for a longer duration and surpasses the sensitivity of a tritium cell of the same age.

The temperatures of column and detector are kept at 50 °C, and 320 °C, respectively. The flow rates of carrier gas back flush and detector purge gases (95% argon + 5% methane or N_2) are kept as 14-18 cm^3 min^{-1}. Gas samples are introduced into a gas sampling loop (size depends upon the sensitivity of the ECD used) through an inlet system. Both CO_2 and water vapours are removed from the gas samples. The two absorbent traps are prepared by packing 10-mm millipore syringe filter holders with Ascarite and $MgClO_4$.

A GC-computer interface is used to plot and measure the peak area. The N_2O standard (500 ppbV) is used as a primary standard.

Calculation of N_2O Flux

Cross-sectional area of the chamber (m^2) = A

Headspace (m) = H

Volume of headspace (L) = 1000 × AH

CH_4 concentration at 0 time (µL L^{-1}) = C_o

CH_4 concentration after time t (µL L^{-1}) = C_t

Change in concentration in time t (µL L^{-1}) = $(C_t - C_o)$

Volume of CH_4 evolved in time t (µL) = $(C_t - C_o) \times 1000$ AH

When t is in hours, then flux (mL m^{-2} h^{-1}) = $[(C_t - C_o) \times AH)/(A \times t)$

Now, 22.4 mL of N_2O is 44 mg at STP

Hence, Flux = $[(C_t - C_o)/t] \times H \times 44/22.4 \times 10000 \times 24$ mg ha^{-1} d^{-1}

Advantages of Closed Chamber Method

- Very small gas fluxes can be measured
- No additional equipment for electric supply is needed
- There is a little disturbance in the site due to the short-time for which the cover is placed for each gas flux estimate
- The chambers are simple and relatively less expensive with a variety of readily available materials, which are inert to the gas of interest
- Chambers can be installed and removed easily, facilitating measurement
- Especially useful for addressing research objectives served by discrete observation in space and time
- In combination with appropriate sample allocations, it is adaptable to a wide variety of studies on the local to global spatial scales
- It is suited to *in situ* as well as laboratory-based studies addressing physical, chemical and biological controls of surface-atmosphere trace gas exchange
- It is good for short deployment period and low exchange rate

Precautions

While using the closed chamber technique for GHG flux measurement, following precautions should be taken:

- Chamber height should be more than 30 cm
- The chamber headspace N_2O concentration at zero hour should be measured accurately. For this, the first air sample inside the chamber should be taken immediately after the chamber placement on the channel/collar in case of cylindrical chambers.
- Air samples should be taken in as short a time as possible to observe a measureable increase in headspace gas concentration. Longer chamber deployment durations may result in negative impacts.

Limitations of the Method and their Addressal

In spite of being simple and popular, the closed chamber method has following limitations:

- Concentrations of gas in the chamber may build up to the levels at which the normal emission rate gets inhibited. However, the problem can be minimized by using shorter collection periods.
- Closed chambers alter the atmospheric pressure fluctuations, which are found at the soil surface due to the natural turbulence of air movement. Thus, a closed chamber may underestimate the flux of a gas.
- This problem may be overcome by an appropriately designed vent, which allows pressure equilibration in and outside the chamber.
- Variations in temperature may occur in soil and inside the chamber. However, insulating the chamber and covering it with a reflective material can reduce the temperature difference.

For conducting round- the-clock emission measurements and overcoming some of the above limitations, automatic sampling devices are very useful. In these devices, the air samples from the inner space of the gas collecting chamber are replaced by a gas flow system providing a periodic sample transfer to the gas chromatograph. However, the automatic sampling devices are costly and their use is confined to those locations where the laboratory is in the vicinity of the experimental field. The automatic sampling system may be used extensively in the long-term field measurements of GHGs at different experimental stations. The basic components of an automatic sampling system are: Gas collecting chambers (boxes) equipped with removable covers, gas flow system (tubing, pump), sampling unit, analytical unit (GC and integrator), time control and data acquisition systems. It allows continuous round-the-clock and simultaneous measurements at several locations for the entire growing season, as is necessary for obtaining data on diurnal and seasonal variations in emission rates under the field conditions.

Practical Considerations to Reduce the Uncertainties

- **Number of chambers:** Due to high spatial variability, the more the number of chambers, the less is the uncertainty.
- **Sampling frequency:** Due to high temporal variability, the more often we sample, the less is the uncertainty.
- **Chamber size:** Due to high microscale variability, bigger is usually better.
- **Chamber deployment time:** Longer period of sampling results in better precision; too long, however, may yield sampling artefacts.

Measurement of Carbon Dioxide Emission from Soil

For the quantitative analysis of CO_2 emission from soil, four methods are used: (1) Alkali trap method, (2) Soil respirator method, (3) Infrared gas analyzer method, and (4) Closed-chamber method.

(1) Alkali Trap Method

In this method, CO_2 is trapped in aqueous solution of alkali (usually KOH or NaOH), and is precipitated as $BaCO_3$ by adding $BaCl_2$ in excess. The precipitate is collected, washed, dried and weighed. The volumetric estimation of CO_2 trapped in aqueous alkali is a popular method because of its simplicity and high degree of sensitivity. For measurement of CO_2 evolution, alkali solution of a known concentration is placed in an open jar on the soil surface, and the area to be measured is covered with a metal cylinder closed at the upper end. The CO_2 evolved from the soil surface is trapped in the cylinder and remains confined there until it is absorbed by the alkali. After a certain period of time, the alkali is removed and its unreacted portion is determined by titration. By subtraction, the amount of CO_2 that combined with the alkali is determined.

A CO_2 trap is prepared by pipetting 20 mL of 1*N* NaOH into a glass jar which is placed on a tripod stand. Immediately, a metal cylinder is placed over the alkali trap, and pressed at the edges by about 2 cm into the surface of the soil. The cylinder should be shielded from the direct sunlight by covering with either a sheet of wood or a piece of aluminum foil. After exposure of the alkali for 2-4 hours, the jar is removed, covered with lids (airtight seal), and brought to the laboratory for analysis. Controls for this experiment consist of jars of alkali that are incubated in the field in completely sealed metal cylinders by closing the open ends with tightly fitting lids. The airtight seal between lid and cylinder can be obtained by smearing the edge with silicon grease. The alkali solutions from the controls and those exposed to the soil air are titrated to determine the quantity of alkali that has not reacted with CO_2. For this purpose, excess $BaCl_2$ is added to the NaOH solution to precipitate the carbonate as insoluble $BaCO_3$. A few drops of phenolphthalein are added as indicator, and the solution is titrated with aq. HCl directly in the jar. The acid should be added slowly to avoid contact with and possible dissolution of the precipitated $BaCO_3$. The volume of acid needed to neutrilize the alkali is noted. The amount of CO_2 evolved from the soil during exposure to alkali may be calculated using formula (1):

$$\text{Milligrams of C or } CO_2 = (B - V)\, NE \qquad \ldots(1)$$

where, *B* = volume (mL) of acid needed to titrate NaOH in the jar from the control cylinder, *V* = volume (mL) of acid needed to titrate the NaOH in the jar exposed to the soil atmosphere, *N* = normality of the acid, and E = equivalent weight of acid. To express the data in terms of carbon, *E* = 6; to express it as CO_2, E = 22. Once the milligrams of CO_2-C or CO_2 have been determined, the data are conveniently expressed as mg of CO_2 m^{-2} h^{-1}.

(2) Soil Respirator Method

The soil respiration, i.e., flux of CO_2 per unit area per unit time, is measured by placing a closed-chamber on the soil and measuring the rate of increase in the CO_2 concentration inside the chamber. The soil respiration system consists of a soil respiration chamber (SRC) and an environmental gas monitor (EGM). For soil respiration, a chamber of known volume is placed on the soil and the rate of increase in CO_2 concentration within the chamber is monitored. With this system, the air is continuously sampled in a closed circuit through the EGM and the soil respiration rate is calculated, displayed and recorded by the analyzer. The air within the chamber is carefully mixed to ensure representative sampling without generating pressure differences, which would affect the evolution of CO_2 from the soil surface.

It is assumed that the rate of increase in CO_2 concentration is linear, though any leakage will cause a decline in its concentration with time. A quadratic equation is fitted to the relationship between the increasing CO_2 concentration and elapsed time. The flux of CO_2 per unit area and per unit time is measured using Equation (2):

$$R = \frac{(C_n - C_o)}{T_n} \times \frac{V}{A} \qquad \ldots(2)$$

where, R is the soil respiration rate (flux of CO_2 per unit area per unit time), C_o is the CO_2 concentration at zero time i.e. T=0 and C_n is the concentration at the time T_n, A is the area of soil exposed, and V is the total volume of the chamber.

(3) Infra-red Analysis Method

Carbon dioxide can be sampled and analysed using infra red-based continuous soil CO_2 flux analyser (LI-8100). The LI-8100 system can be used with a 20 cm short- term survey chamber to obtain soil CO_2 flux. The closed-chamber is placed on the soil and the rate of increase in CO_2 concentration in the chamber is used to determine the soil flux. CO_2 diffuses out of the soil in response to the concentration gradient between the soil pore spaces and the atmosphere. As CO_2 concentration in the chamber increases, the concentration gradient between soil and the chamber air decreases. This causes the measured soil CO_2 flux to decrease exponentially with time. The desired value of the soil flux can be determined when the concentration of CO_2 is same in the chamber and ambient atmosphere. The flux can be estimated using the initial slope of a fitted exponential curve at the ambient CO_2 concentration. This is done to minimize the impact of the altered CO_2 concentration gradient across the soil surface after chamber is closed.

(4) Closed Chamber Method

The CO_2 flux from the soil using closed-chambers can be determined by collecting gas samples periodically from the chambers and measuring the change in concentration of a gas with time during the period of linear concentration change similar to sampling of methane and nitrous oxide. The analysis can be done in gas chromatograph fitted with FID (discussed above) and a methanizer. The methanizer consists of a 6" × 1/8" stainless steel tube which is mounted alongside the edge of a heated valve oven, and thermostated to 380ºC. The tube is packed with a special nickel/zinc/Pt-Pd catalyst powder. Column effluent is flushed with 20 mL/min of hydrogen prior to the methanizer entrance. Under these conditions, CO and CO_2 are converted to methane while passing through the methanizer. Hydrocarbons such as methane, ethane and propane pass through the methanizer unaffected. The CO and CO_2 being converted to methane, can be detected by the FID down to 1 ppm. The concentration of CO_2 is about 380 µL L^{-1} in air, but CH_4 is only about 1.8 µL L^{-1}, the CO_2 response (after conversion to CH_4) on the FID is much stronger than of CH_4 (in air samples). Calculation of flux can be done similar to methane, as CO_2 is measured as methane. It may be noted that methanizer tubes can be poisoned by the large amounts of sulphur gases.

The CO_2 concentration in gas samples can also be analyzed using a gas chromatograph equipped with a thermal conductivity detector (TCD) and a Hayesep D column 3-m long and 0.3-cm internal diameter. Helium is used as a carrier gas at a flow rate of 25 cm^3 min^{-1}. Oven and detector temperatures are

50 °C and 150 °C, respectively. Standard CO_2 samples are used for calibration of the GC. Flux (F) of gases (g CO_2-C m^{-2} day^{-1}) can be computed by Equation (3):

$$F = (\Delta g/\Delta t)\ (V/A)k \qquad \ldots(3)$$

where, $\Delta g/\Delta t$ is the linear change in CO_2 concentration inside the chamber (g CO_2-C m^{-3} min^{-1}); V is the chamber volume (m^3); A is the surface area of the chamber (m^2), and k is the time conversion factor (1440 min day^{-1}). Chamber gas concentration can be converted from molar mixing ratio (ppm) determined by GC analysis to mass per volume by assuming ideal gas relations. Hourly CO_2 fluxes are calculated from the time vs. concentration data using linear regression.

Global Warming Potential

The global warming potential (GWP) is an index developed to compare the strengths of different GHGs in reusing temperature on a common basis. CO_2 is used as the reference gas to compare the ability of a GHG to trap atmospheric heat relative to CO_2. Thus, GHG emissions are commonly reported as CO_2 equivalents (e.g. in tonnes of CO_2 eq.). The GWP is a time integrated factor, thus the GWP for a particular gas depends upon the time period selected. A 100-year GWP is the standard that has been broadly accepted for GHG reporting (Table 1). The GWP of agricultural soils may be calculated using Equation (4) (IPCC, 2007):

$$GWP = CO_2 + CH_4 * 25 + N_2O * 298 \qquad \ldots(4)$$

References

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