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Review Article

Impact of Tropospheric Ozone on Agroecosystem: An Assessment

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ABSTRACT

Tropospheric ozone (O_3) is an important component of global and regional climate change. A higher ozone concentration in rural and peri-urban agricultural region poses threat to food production in developing countries including India. Unlike all other climatically important trace gases, ozone is toxic, and increase in its concentration results in serious environmental damage, as well as serious threat to human health. Chronic and detrimental effects of tropospheric ozone have been observed on ecosystem. The interactions between O_3 and other climatic factors are also important since O_3 impacts on crop yield are influenced through associated environmental factors, in particular drought, humidity and temperature. Therefore changes in climatic conditions could exacerbate future crop yield losses resulting from O_3. Assessing the regional impacts of ozone either through exposure-yield relationship or stomatal flux based models will help formulate appropriate management strategies in agriculture to address this issue. This review article discusses the process of ozone formation, its impact on vegetation and soil properties, interaction of ozone with other environmental factors, ozone risk assessment, and management strategies in agriculture to reduce its detrimental effect. This article further highlights future research issues and thrust areas in India.

Key word: Tropospheric ozone, Impact, Assessment, Climate change, Vegetation

Introduction

Ozone (O_3) is present throughout the atmosphere and can be either positive or negative depending on where it is found. The stratosphere (15-50 km) has the largest fraction and concentrations of ozone (90%, Colls, 1997). Stratospheric O_3 is important as it regulates the window for the transmittance of ultraviolet light to the surface of the earth. Hence, reductions in stratospheric O_3 in general and in Polar regions, particularly the Antarctic "ozone hole", are of major concern. In the troposphere (0-15 km) ozone is a toxic pollutant of global importance and it is a major constituent of photochemical smog. Interest in pollutant ozone (O_3) and in its effects on living organisms has increased in the last few decades as a consequence of the rise in concentration at ground-level and of the widening of its diffusion areas (Ashmore, 2005). About 30 years ago, it was recognized that the increase in tropospheric ozone from air pollution (NO_x, CO and others) is an important greenhouse forcing term. In India, economic growth will require more energy production, which will result in increased production of NOx and VOCs precursors for O_3 formation (Ghude *et al.*, 2008). Due to rapid economic development during the past decades, surface O_3 increased at an annual rate of 0.5%-2% (Vingarzan, 2004) and has now reached a global mean of approximately 50 ppb (8-h summer seasonal average) (Anonymous, 2008). While O_3 is often originated in urban areas, it can be transported long distances on prevailing winds. High O_3 concentration in rural and remote regions

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has been reported to affect the growth and productivity of agricultural crops and forests (Ashmore, 2005; Agrawal *et al*., 2005).

Tropospheric O_3 is known to be highly phytotoxic. Appropriate exposures to O_3 can result in both acute (symptomatic) and chronic (changes in growth, yield or productivity and quality) effects (Ghude *et al*., 2008). The adverse effects of ozone on plants were first identified in the 1950s, and it is now recognized as the most important air pollutant, affecting human health and materials, as well as vegetation and soil. Chronic effects are of great concern in terms of both crops and forests. Full 50% of the global forested lands have been predicted to be exposed to O_3 higher than 60 ppb by 2100 (Percy *et al*., 2002). The current levels of the pollutant are high enough to exceed the tolerance threshold of many plant organisms thus impairing plant growth, reducing crop yields and altering the composition of plant communities (Ashmore, 2005; Agrawal, 2005). This review therefore highlights tropospheric ozone as an important component of climate change research in the context of its impact on ecosystem, ozone risks assessment and management strategies to cope with adverse effects.

Formation and Concentration of Ozone in Troposphere

Tropospheric O_3 is predominantly produced by photochemical reactions involving precursors generated by natural processes and to a much larger extent by human activities (Figure 1). Tropospheric $O_{3,}$ a secondary pollutant, are formed via the photochemical oxidation of carbon monoxide (CO), methane (CH_4) or non-methane volatile organic compounds (NMVOCs) (mainly from vehicles, solvents and industry) in the presence of nitrogen oxides (NOx, NOx = NO + NO_2) (IPCC, 2001; Unger *et al*., 2006). The atmospheric chemistry involved in ozone formation is complex (see PORG 1997). It takes time for the ozone to accumulate as the chemical reactions involved are quite slow. Peak ozone formation takes place downwind of precursor sources in sunny weather with low wind speeds. Ozone concentrations are influenced by sources, meteorology and chemical reactions over local, regional and hemispherical distances. As a result there is considerable variation in spatial and temporal ozone distribution and concentrations. Although most ozone precursors are found in urban areas, concentrations of tropospheric ozone tend to be higher away from the towns (Agrawal

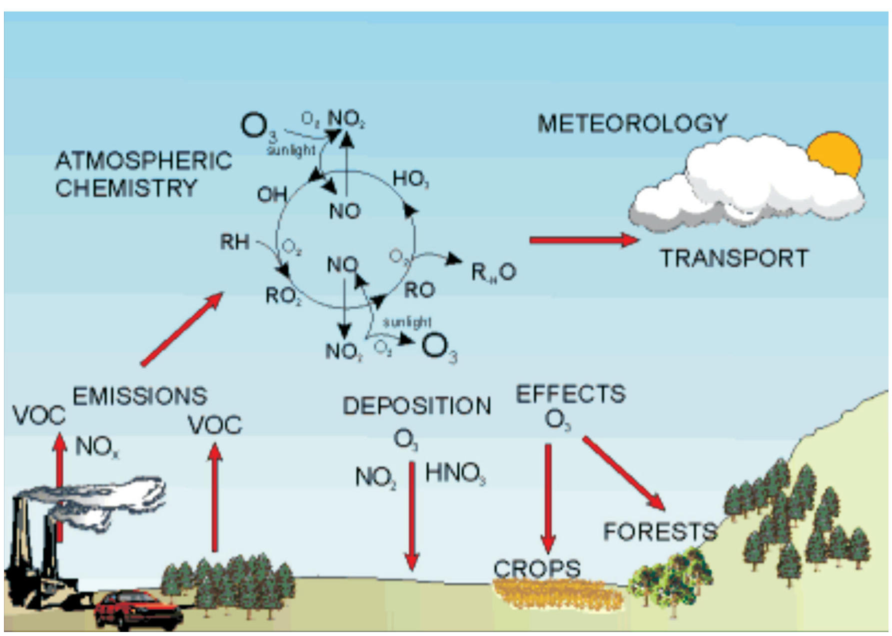

Fig. 1. Troposphere Ozone formation and transportation downwind of precursor formation (Adapted from http://www.globalchange.umich.edu)

et al., 2005; Ghude *et al*., 2008). Partly, this is a consequence of nitrogen oxide (NO) reacting with ozone to produce nitrogen dioxide (NO_2, itself a pollutant) and oxygen, e.g. in the UK, ozone concentrations are strongly influenced by emissions of precursors in Europe.

On global level, tropospheric O_3 concentrations have increased from pre-industrial levels of 10-20 ppb to the current 40 ppb. Significantly, increase in peak concentration may be declining, but the background level of O_3 continues to rise. Fischman (1991) reported long-term records of tropospheric ozone measurements in the Northern Hemisphere suggesting that it is increasing at a rate of 1 to 2 percent per year. Because of this, it is argued that the amount of atmospheric warming due to increasing tropospheric ozone is comparable to, or possibly even greater than, the amount of warming due to the increase in carbon dioxide. Several studies have used global models to examine the impacts of continued increased emissions of nitrogen oxides on future ozone concentrations (e.g. Collins *et al*., 2000; Ghude *et al*., 2008). Models predicted that tropospheric O_3 could rise 20–25% between 2015 and 2050, and further increase by 40–60% by 2100 if current emission trends continue (Meehl *et al*., 2007). Projections of future global O_3 trends show that O_3 concentrations will increase rapidly over the next 20 to 30 years with South Asia projected to experience the highest increase in surface O_3 (average annual increases of 7.2 ppb occurring by 2030) (Dentener *et al*., 2006).

Increase in O_3 concentrations (23±9 ppbv) in May and lower concentrations (17±7 ppbv) in October at Tranquebar (Debaje *et al.,* 2010) and in Delhi (Ghude *et al*., 2008) due to the increase in NO*x* and other O_3 precursor emissions by different sources in the proximity of these sites. High concentrations of O_3 are associated with hot sunny weather. Such high concentrations of O_3 are frequently observed in tropical areas where conditions are favorable for O_3 formation (Tiwari *et al*., 2008). Debaje *et al*. (2010) observed monthly average of daytime maximum of O_3 mixing ratio ranged from 14 to 57 parts per billion by volume (ppbv) with an annual average of about 20 ppbv at Ahmednagar (19.1°N, 74.8°E, 657 m above sea level). They estimated winter wheat and summer crop yield reduction by 10% and 15%, respectively from present O_3 pollution level associated with AOT40 (accumulation exposure of O_3concentration over a threshold of 40 ppbv) index values 7370-9150 ppbv h in rural areas.

Ozone and Other Environmental Factors

In a natural ecosystem, many other factors can ameliorate or magnify the extent of ozone injury at various times and places such as soil moisture, presence of other air pollutants, insects or diseases, and other environmental stresses. The interactions between O_3 and climate change are also important since O_3 impacts on crop yield are influenced by environmental factors, in particular drought, humidity and temperature; as such changes in climatic conditions could exacerbate future crop yield losses resulting from O_3 (Ashmore, 2005).

The most important external growth factors which influence the sensitivity of plants to ozone are: climatic factors like temperature, humidity, wind speed and solar radiation; nutritional factors like soil moisture and nutrient supply; infection by pathogens. These factors, as well as others, interact creating a complex system which can mask the real nature of ozone influence on plants. The influence of factors like vapour pressure deficit (VPD), temperature, soil humidity and solar radiation has been pointed out both by experiments and models (Ashmore, 2005; Meehl *et al*., 2007). However, the relative weight of such factors is not so clear, and the relationship between parameter variations and the response of plants to pollutant variations is not always linear. With reference to temperature, it is clear that the different degree of plant sensitivity to ozone cannot be determined considering the variation of temperature only during the sunlight period, since daily temperatures are affected also by different nightly patterns too (Pleijel *et al*., 2007). The exposure temperature is usually assumed as reference temperature, but during soybean experiments the growth temperature has resulted in as an important factor to be taken into account. Multi-variable statistical models (artificial neural network) have confirmed the importance of both the average temperature during sunlight and the daily average temperature, as regards the response of plants to ozone. These temperatures resulted in an influence on the response of plants to ozone much greater than the temperature during the period of higher ozone concentration. The increase in the exposure temperature is generally believed to cause an increase in foliar damage. However, the response is variable and depends on species and soil moisture (Ashmore, 2005; Pleijel *et al*., 2007). A decrease of VPD usually leads to an increase of stomatal conductance which in turns leads to a higher ozone flux toward plants and finally to greater foliar damage.

Impacts of Ozone

Vegetation

Elevated O_3 tends to decrease biomass production by producing active oxygen species after diffusing into plant cells. The detrimental effect of ozone was progressively greater as the average daily O_3 increased, with very few exceptions. The impact of O_3 increased with developmental stages, with the largest detrimental impact during grain filling in wheat (Feng *et al*., 2010). Elevated O_3 tend to alter C partitioning to defense processes by stimulating the phenylpropanoid pathway, which results in increased production of phenolic compounds in soybean leaves (Booker *et al*., 1998). Because of the co-occurrence of high O_3 levels during warm weather, combined with reduced soil moisture, interactions between O_3 stress and water use efficiency (WUE) are important. Reduced leaf WUE in response to O_3 was found, for instance, in wheat (Saurer *et al*., 1991) and soybean (Vozzo *et al*., 1995). This effect may be linked to direct negative effects of O_3 on stomatal functioning, or a stronger sensitivity of photosynthetic CO_2 fixation relative to the stomatal conductance to water vapor (Saurer *et al*., 1991). But because of a concurrent reduction in crop biomass, O_3 is not likely having an effect on total crop water consumption. Conversely, under dry conditions, stomatal limitation of O_3 uptake is higher and thus the plants are partially protected from short-term O_3 impacts. Plant species and cultivars also differ in sensitivity to ozone, and competitive relationships between the different components of a pasture have been shown to be altered by ozone. Short term and long term critical levels have been defined by various workers for protection of crops against visible injury. Critical levels have been defined as those pollutant concentrations in the atmosphere above which direct adverse effects on receptors, such as plants, ecosystems or materials, may occur according to present knowledge (UN/ECE, 1988). These critical levels are expressed as cumulative exposures over the threshold concentration of 40 nl l^{-1} h ozone during daylight hours and are referred to as AOT40. Recently, short-term critical levels of 200 and 500 nl l^{-1} h ozone (accumulated over 5 consecutive days) for injury development have been defined when mean VPD (9.30–16.30 h) is below or above 1.5 kPa, respectively. A long-term critical level of 3000 nl l^{-1} h for a 3-month period has been proposed to protect crops against significant yield reductions (Kärenlampi, L. and Skärby, 1996).

The first report of ozone injury to a crop plant in India was reported by Bambawale (1986). Evidence is presented to show that a serious leaf spot disease of potato which appeared each year in the Punjab since 1978 was primarily due to ozone. The symptoms of the leaf spot were similar to the ozone stipple of potato reported in the U.S.A. Activated charcoal and ethylenediurea effectively controlled the spots. Elevated ozone in the atmosphere was detected with the help of bioindicators *Nicotiana tabacum* var. Bel-W3 and potato variety Cherokee. Subsequently there have been reports of visible ozone injury on different crops observed by several researchers in India, e.g. in paddy (Rai and Agrawal, 2008; Sarkar and Agrawal, 2010), Beta vulgaris L. (Singh *et al*., 2005; Tiwari and Agrawal, 2009), Vigna mungo L. (Singh *et al*., 2010), Trifolium repens L. (Singh *et al*., 2010), Indian wheat (Singh and Agrawal 2010; Sarkar and Agrawal, 2010) tropical oil crops (Singh *et al*., 2009), carrot (Tiwari and Agrawal, 2010) and linseed (Tripathi *et al*., 2011).

Enhanced UV-B radiation, O_3 and NO_2 reduced biomass, yield (10%), photosynthetic rate, chlorophyll, and catalase activity in wheat at Varanasi (Ambasht and Agrawal, 2003; Sarkar and Agrawal, 2010), Ahmednagar (Debaje *et al.,* 2010) and Eastern Gangetic plains (Rai *et al*., 2007). Cultivar sensitivity to O_3 has been determined for wheat in India using EDU (Agrawal *et al*., 2004; Tiwari *et al*., 2005). Singh *et al*. (2010) reported improvement in various yield attributes under EDU application on wheat in Eastern Gangetic plains of India suggesting thereby its protective nature against ozone. They further observed that 400ppm EDU was most effective in alleviating the negative effect of O_3 on wheat and its application throughout the plant life is most beneficial for protection against O_3 compared to particular growth stage.

Soil Properties

Besides the direct impacts of O_3 exposure on the aboveground plant organs, current levels of O_3 are capable of altering the timing and quantity of carbon fluxes to soils (Andersen, 2003; Loya *et al*., 2003) and methane emissions (e.g. Niemi *et al*., 2002). Exposure to ozone will also reduce the land carbon sink due to reductions in plant/ tree growth, offsetting the positive effect due increase in carbon dioxide concentrations. Caused by relative inaccessibility of belowground there is a limited understanding of possible effects of ozone on root and soil processes (Andersen, 2003). Negative effect of high ozone concentration is suppressed by dry periods in summer. This is corroborated by the findings of Gorissen *et al.* (1994) who reported that in Douglas-fir translocation of carbon to the root-soil compartment was additively affected by ozone and low soil water content. He further suggested that dry periods in summer combined with high ozone concentrations cause the greatest reduction in the supply of carbon compounds to the root-soil compartment.

Loya *et al.* (2003) found that the rates of formation of total and acid-insoluble soil carbon are reduced by 50 per cent relative to the amounts entering the soil when the forests were exposed to increased carbon dioxide alone, with ambient concentrations of ozone and carbon dioxide both raised by 50 per cent. They further suggested that, in a world with elevated atmospheric carbon dioxide concentration, global-scale reductions in plant productivity due to elevated ozone levels will also lower soil carbon formation rates significantly. Felzer *et al.* (2002) incorporated empirical equations derived for trees (hardwoods and pines) and crops into the Terrestrial Ecosystem Model version 4.3 (TEM 4.3) to explore the effects of ozone on net primary production and carbon sequestration across the conterminous United States. Carbon sequestration during the 1980s was reduced by 30 to 70 Tg C yr^{-1} with the presence of ozone which was 5 to 23% of recent estimates of the total carbon sequestration for the U.S. Hofmockel *et al.* (2011) also reported elevated O_3 significantly reducing cPOM N (particulate organic matter nitrogen) by 15% and significantly increasing the C:N ratio by 7%. Long-term exposure to elevated CO_2 and O_3 can not only change biotic factor controlling litter decomposition, but also alter the abiotic decomposition environment, such as soil moisture, soil temperature and soil aggregates formation. All these factors play important roles in affecting soil C and nutrient cycling, and need to be considered when trying to understand how elevated CO_2 and O_3 affect litter decomposition.

Disease and Pest Incidence

Ozone effects on plants lead to altered disease susceptibility, but the effect is variable. As observed by von Tiedemann *et al.* (1991), powdery mildew (*Erysiphe graminis* DC. f. sp. *tritici* Marchal), leaf spot disease (*Septoria nodorum* Berk.), and spot blotch following inoculation with *Bipolaris sorokiniana.* Sacc. were significantly enhanced by exposure of wheat flag leaves to O_3. Conversely, Plazek *et al.* (2001) found a positive effect of O_3 on resistance of barley and fescue to *B sorokiniana*, and in rapeseed to *Phoma lingam*. In a more recent study, leaf rust disease (*Puccinia recondite* f. sp. *tritici*) on wheat leaves was strongly inhibited by O_3, but was largely unaffected by elevated CO_2 both in the presence and absence of O_3 stress (von Tiedemann and Firsching, 2000). In the field, the incidence of powdery mildew was reduced because of negative effects of O_3 on canopy structure resulting in a drier canopy microclimate, while infections caused by facultative pathogens were generally increased (Fuhrer, unpublished data). This would suggest that under altered climatic conditions favoring infection pressure, plants weakened by O_3 stress may be particularly susceptible. But the interaction between O_3 and pathogens may be determined primarily by the timing of O_3 exposure relative to the presence of the inoculation. Sandermann (2000) suggested that O_3 stress may induce a burst of active oxygen, which triggers the plant defense system in the leaves (systemic acquired resistance, hypersensitive response). Thus, the outcome of plant–pathogen interactions may strongly vary with timing, stage of plant development, predisposing factors, and environmental conditions.

Ozone Risk Assessment

A number of experimental techniques are available to evaluate the chronic effects of O_3 on plants. Among all field evaluation techniques, open-top chambers are the most frequently used method for evaluating the chronic effects of O_3 on vegetables and crops all over the world including India (von Tiedemann *et al*., 1991; Tiwari *et al*., 2006). However OTCs have some chamber effects that alter the actual results because chamber environment differs in some respect from ambient conditions such as light intensity is reduced inside the chambers, relative humidity increases and sometimes greenhouse gases get accumulated in chambers in some specific plants which could affect the results of the study (Manning, 2005). The National Crop Loss Assessment Program (NCLAN) of the United States is the largest such effort. However, given the limitations of the open-top chambers and the experimental aspects of NCLAN, its results must be interpreted with caution. On the other hand, acute effects can be evaluated with less complexity through the use of biological indicator plants. The numerical modelling of such effects is also far less complicated than establishing numerical cause and effects relationships for chronic effects. Two most widely used methods in assessing the regional impacts are first concentration based i.e exposure-yield respone (AOT40 index) and second modeled ozone flux. The first critical levels for ozone were based on the concept of AOT40 (The sum of the differences between the hourly mean ozone concentration (in ppb) and 40 ppb when the concentration exceeds 40 ppb during daylight hours, accumulated over a stated time period). However, several important limitations and uncertainties have been recognized for using AOT40. In particular, the real impacts of ozone depends on the amount of ozone reaching the sites of damage within the leaf, whereas AOT40-based critical levels only consider the ozone concentration at the top of the canopy (Ashmore, 2005; Pleijel *et al*., 2007). Ozone critical levels are defined for crops, (semi-) natural vegetation and forest trees using the ozone parameter AOT40. However, these exposure-response relationships cannot reliably be used to compare the impacts of ozone in different locations, or in future years, because the different climatic conditions may lead to variable impacts of the same concentrations of ozone (Ashmore, 2005). This is significant because, in the field, the highest ozone concentrations tend to occur under meteorological conditions which limit the flux of ozone into the leaves, because of the high resistance to ozone flux. However, AOT40 measures continue to be used where fluxed based models are not available (Pleijel *et al*., 2007).

Therefore, AOT40-based critical levels are replaced or supplemented with models of absorbed dose or flux into the leaf on the basis that these provide a more realistic basis for ozone risk assessment (Pleijel *et al*., 2007). Stomatal flux of ozone describes the movement of ozone from the outside of a leaf, through the stomatal pore and into the air spaces inside. It is modelled by predicting the transport of ozone through the stomatal pores per unit of leaf area at any moment in time. Stomatal uptake of ozone is determined by the influence of climatic factors (Vapour Pressure Deficit (VPD), temperature and light), soil factors (Soil Moisture Deficit (SMD)), ozone concentration and plant development stage (phenology) on the width of the stomatal pore. The development of flux-based models linked to effects on carbon assimilation and allocation offer a basis to improve the capacity for risk assessment, but there are a range of potential impacts of ozone, especially at the ecosystem level, for which the necessary mechanistic understanding does not exist to allow their inclusion in local or global risk assessments. Despite limitations attached to the use of these techniques. The results obtained are valuable if interpreted in the appropriate context.

Some Important Terminologies used in Models

Fst : The instantaneous **F**lux of ozone through the **st**omatal pores per unit projected leaf area (PLA) in nmol m^{-2} PLA s^{-1}. Fst can be defined for any part of the plant, or the whole leaf area of the plant, but for this report, Fst refers specifically to the sunlit leaves at the top of the plant canopy. Fst is normally calculated from hourly mean values and is regarded as the hourly mean flux of ozone through the stomata.

AFstY: The **A**ccumulated **F**lux above a flux threshold of **Y** nmol m^{-2} s^{-1}, accumulated over a stated time period during daylight hours, units mmol m^{-2} PLA.

CLef : The stomatal flux-based **C**ritical **L**evel of ozone, in mmol m^{-2} PLA, is the cumulative stomatal flux of ozone, AFstY, above which direct adverse effects may occur according to present knowledge.

Management Strategies to Overcome Ozone Injury

Factors which limit productivity today are also subject to future changes, including biotic and abiotic stresses, and the direct effects of increased CO_2, O_3 or temperature on the plants may be of less importance than effects on the plants' ability to cope with the change in factors limiting or reducing yields. This raises the question of how management may need to adapt in order to mitigate the change in these factors under future atmospheric conditions. Major management adjustments could be necessary in terms of resource management. Irrigation management may need to be adapted to changes in patterns and amounts of precipitation. Williams *et al.* (2001) suggested that in order to preserve soil quality adaptations may include systems that are less prone to erosion and produce higher yields of crops as well as those more adapted to warmer, wetter springs, and hotter summers. Shifts in the selection of crop cultivars may be necessary to adapt to shorter growing seasons offered at a place and adjustments of suitable planting dates (Dale, 1997). Because of the influence of elevated CO_2, O_3 and increasing temperatures on nitrogen cycling, adjustments are also necessary in terms of nutrient management. N supplementation counteracted the O_3-induced senescence but did not modifiy the effects on nutritive quality in *Briza maxima* a pasture in Mediterranean areas (Sanz *et al.,* 2011). Timing and amount of fertilizer application depends on both crop demand and mineralization–immobilization processes, which are influenced by climate and CO_2. Furthermore, the use of crops with improved genetics may become increasingly important, and traditional breeding and seed production may produce specific agronomical, morphological and physiological plant traits which could increase or stabilize yields in stressful environments (Kobiljski and Dencic, 2001). However, to define the targets for breeding programs, or genetic improvements, it is important to understand the key plant characteristics. For instance, to cope with increasing risks form O_3 pollution in regions with growing food demands, the use of crops with improved O_3 tolerance would be an option. As discussed by Fuhrer and Booker (Fuhrer and Booker, 2003) this could be achieved by raising the capacity of plant's to detoxify activated oxygen species in the apoplast. Recent research initiatives have been directed towards increasing the understanding of potential global climate change impacts on plant pests and developing better predictive capabilities (Scherm *et al.*, 2000). Because insect and plant species show individualistic responses to temperature, CO_2 and other factors, it is expected that climate change will affect the temporal and spatial association between species interacting at different trophic levels (Percy *et al.,* 2002).

Application of ethylene diurea (EDU) may provide plants with protection, which could result in increased growth and crop yield. However, the mechanisms by which EDU protects plants from ozone are not yet clearly understood. The effects of EDU reported by various researchers are preliminary, and increased yield in crop plants treated with EDU (Singh and Agrawal, 2010) does not necessarily mean that current levels of ozone are negatively affecting crops. It is possible that the effects observed could be a result of physiological mechanisms unrelated to the protective properties of EDU. Researchers reported that EDU is very effective in delaying plant senescence and leaf abscission without reducing yield. Effects of EDU are not only species specific but show variations among cultivars of the same species, concentration frequency and mode of its application. Feng *et al.* (2010) reported that EDU significantly ameliorated the biomass and yield of crops and grasses, but had no significant effect on tree growth with an exception of stem diameter. EDU applied as a soil drench at a concentration of 200-400 mg/L showed the highest positive effect on crops grown in the field. Overall, intensive agriculture may have the potential to adapt to changing conditions, in contrast to extensive agricultural systems or low-input systems which may be affected more seriously.

Conclusions

Ozone should be considered as a component of global change and priority be given to understanding its interaction with other factors such as CO_2 concentration, water availability and temperature. In stark contrast to the gains in crop productivity made during the Green Revolution, evidence suggests that growth in crop yields in South Asia including India have been declining in over recent years. This has been attributed to a number of factors including declining soil fertility and climate change. The evidence presented here suggests that increasing levels of O_3 are an additional and extremely important factor in this deceleration crop yields. This has serious implications for sustainable agriculture given the pressure on cultivated land area e.g. from diversion of crops for bio-energy production, and increasing demand with the rapidly expanding Indian population. The threat of reduced agricultural yields due to increasing O_3 concentrations may encourage developing countries to increase their energy efficiency and to use multiple energy sources.

Future Thrust

Increasing impacts of O_3 on crops are likely in developing with continuation of industrialization and enhanced emissions of air pollutants. Important researchable issues identified are: (1) changes in the quality of crops used for human nutrition or animal feed, (2) nutrient cycling and nitrogen/ carbon balances in agro-ecosystems, (3) impact on trace gas fluxes and sinks, (4) soil-plant water relationship, (5) below ground carbon fluxes, (6) changes in soil rhizospheric activity (7) changes in biodiversity of crops, pastures and agricultural landscapes, (8) interactions between ozone and other environmental factors that are either directly manipulated by man or indirectly changed as part of global change, (9) processes involved in the initial reactions of ozone with extracellular and cellular components, after entry through the stomata, must be understood, (10) better understanding of plant protection mechanisms against ozone to reduce the impacts, (11) despite the progress made in modelling ozone fluxes, the fate of ozone once it reaches the canopy remains uncertain. In addition to the stomatal flux, the total ozone flux for a specific land cover also includes the parallel flux to external plant surfaces, and the flux to the soil. The partitioning of the total flux into these components, in relationship to the specific surface characteristics, is not fully understood. Future research must address these issues on climate change and tropospheric ozone together in India.

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