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PJBS

ISSN 1028-8880

Pakistan Journal of Biological Sciences

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Pakistan Journal of Biological Sciences 8 (11): 1630-1638, 2005
ISSN 1028-8880

Agriculture and Global Warming: Evapotranspiration as an Important Factor Compared to CO_2

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Abstract: Over the past few decades, global warming vis-à-vis elevated CO_2 and other greenhouse gases (GHGs) has remained an issue of concern for researchers, environmentalists and policy makers. Fossil fuels have been blamed for most of the rise in atmospheric CO_2 over the recent past in spite of the fact that water vapour (WV) is the predominant greenhouse gas (atmospheric concentration of 1-2% i.e., 27-54 times that of CO_2 and >95% contribution to greenhouse effect) and mostly of natural origin. Incidentally, most if not all, statistics on GHGs overlooks WV creating the impression of human intervention (anthropogenic) as the dominant contributor to global warming. Similarly, role of evapotranspiration (ET) from the vegetated land in elevating the atmospheric concentration of WV is almost completely overlooked. According to highly conservative estimates ET from agricultural lands is responsible for adding $>22\times10^{12}$ t year^{-1} to the total atmospheric water of 30-60$\times0^{12}$ t. These are astonishing high contributions to atmospheric WV that need to be considered when assessing anthropogenic (agricultural activity is certainly an anthropogenic activity) aspects of global warming. This review takes an account of these factors ultimately suggesting that i) ET is capable of raising the atmospheric WV concentration significantly and ii) evolution and introduction of crop types more efficient in water use may help resolve the problem.

Key words: Atmosphere, elevated CO_2, fossil fuels, green house gases, water vapour

INTRODUCTION

During about 4 billion years of life on this planet, the climate has swung between ice ages and warm periods. The main source of warmth on earth is the solar radiation one-third of which is reflected and the rest is absorbed by different components of the climate system that includes atmosphere, oceans, land surface and biota. The surface of the earth gets hot after absorbing the energy and radiates the later back into the atmosphere where part of it is absorbed by some of the gases. The heat energy (infrared radiation) gained by the gases is radiated back to the earth's surface thereby keeping the surface temperature higher than it should be in the absence of these gases or the atmosphere so to say. This process is termed greenhouse effect and the gases that contribute towards this effect as the greenhouse gases. The term greenhouse is used to describe this phenomenon since these gases act like the glass (although these gases are relatively transparent to sunlight, they slow down the escape of heat from the Earth) of a greenhouse to trap heat and maintain higher interior temperatures than would normally occur. This is a natural effect which keeps the Earth's temperature at a level necessary to support life.

Generally, earth's atmosphere has been in chemical balance and its composition changed slowly with changes in geology and life. Now, growing population and the by-products of civilization are upsetting this balance. Indeed, several natural and human activities have the potential to change the balance between the energy absorbed and emitted by earth. The natural contributions to the disturbance in balance come from i) small changes in solar radiation and ii) volcanic eruptions that inject huge clouds of sulphur-containing gases with a potential to cool the earth surface and the atmosphere. The human intervention is in terms of emissions from land-use changes and industrial practices that add or remove greenhouse gases thereby changing atmospheric absorption of radiation and hence conspicuous increase in temperatures. The net consequences of global warming are expected to include increased rainfall, melting polar ice caps, rising ocean levels, increased flooding, widespread crop failure and endangering organisms. It is generally agreed, however, that some degree of climate change is inevitable, with associated impacts. Hence, active adaptation strategies should be an integral part of climate change responses.

Coping with climate change and a warmer world will mean changing the way we live. For example, urban planning in coastal areas will need to consider beach erosion and lagoon flooding caused by rising sea levels. In some regions, buildings will also need to be designed

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to cope with more intense wind gusts and possible storm surges. Areas prone to flooding, for example, may need to increase the size of street gutters and water storages to carry large volumes of water, while drier areas will need to use water more wisely. Some farmers may need to switch to different crops or varieties of crops to cope with climatic changes. It is evident that putting in place strategies to adapt to climate change has the potential to reduce its adverse impacts as well as to capture its possible benefits. Adapting to climate change will, however, incur costs and is not likely to prevent all damage.

Greenhouse gases of significance include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), ozone (O_3); water vapour not withstanding. Respective contribution of these gases to global warming is estimated at 76, 13, 6 and 5%. The difference is attributable mainly to the quantity of these gases in the atmosphere. Otherwise, CH_4 and N_2O are 25 and >300 times more efficient in absorbing infrared radiation as compared to CO_2 or H_2O; the potential of CFCs being several thousand folds higher and so is their greenhouse warming potential (GWP). Although most of these gases (except for CFCs and their substitutes) occur naturally, their concentration has increased significantly over the last 200 years and continues to increase due to human activities. Of these, CO_2, CH_4 and N_2O are associated more closely with agricultural activities and contribute 26, 60 and 14%, respectively to the total greenhouse gases. The major culprit in enhancing atmospheric CO_2 concentrations is, however, considered to be ever increasing fossil fuel burning. With increase in population, especially of under-developed countries and the ambition of improving standard of living (fossil fuel consumption per capita being used as a routine parameter), there is every likelihood that CO_2 concentration of the atmosphere will continue rising. Due to increased awareness and hike in fossil fuel price, however, there is an increasing tendency for fossil fuel-driven CO_2 emissions to falter. Already, such tendency is reported to exist in developed countries, while the developing countries are on the path of increasing use of fossil fuels and hence contributing more to the CO_2[1].

It is interesting to note that CO_2 is considered to be the main culprit in global warming, while hardly any mention is made of the role of water vapour (WV) that accounts for 95% of the greenhouse effect[2]. This is particularly important in view of the fact that a significant proportion of the atmospheric WV originates from the vegetation especially the agricultural crops production of which has increased substantially (average 60% for different crops) over the past few decades. This review presents analysis of the relative significance to global warming of CO_2 and WV originating from agricultural activity.

Carbon dioxide levels in the atmosphere: Views about the composition of earlier atmospheres are conflicting, but the last 30 million years seem to have faced typically low levels of CO_2. Carbonate concentrations and $\delta^{13}C$ values in the mineral goethite suggest that the first terrestrial plants, living about 420 million years ago, faced CO_2 partial pressures that were 16-fold higher than the present[3]. Although major atmospheric changes are not novel, previously they occurred over thousands to millions of years, not decades. For the past two millennia, the CO_2 content of the earth's atmosphere has been fairly constant averaging 280 ppm. With rapid industrialization, however, this equilibrium has been disturbed over the last 250 years. Presently, it stands at around 370 ppm, showing an increase of 100 ppm since 1700. During the last 25 years alone, a rise of *ca* 60 ppm in CO_2 concentration has been recorded, while an increase of *ca* 25 ppm occurred between the years 1900 and 1950 (Fig. 1). Hence, in less than 50 years, CO_2 concentration has increased from 316 to the present levels of 370 ppm with a current increase of about 1.8 ppm per annum[4].

Human development vis-à-vis fossil fuel consumption and atmospheric CO_2: The CO_2 concentration of the air started increasing as humanity embarked upon a course of unprecedented economic development that coincided with the increase in the burning of fossil fuels such as coal, gas and oil, expansion of agriculture, urbanization and deforestation. Figure 1 shows the relationship between human population, fossil fuel burning, global temperature and atmospheric CO_2 levels. It is the human activities in terms of fossil fuel burning generating 5-8 Gt C $year^{-1}$ that has made the major difference to the atmospheric CO_2 concentration over the past few decades. Interestingly, the increase in atmospheric CO_2 levels has coincided with human development that is bound to improve, especially in the present day developing countries with fast growing populations. As high population countries such as Nigeria, India, Pakistan, China and Indonesia increase their standard of living, the energy consumption (90% produced by burning fossil fuels) will have a major implication for global CO_2 levels. The fossil fuel contributes 11.4 Gt ha^{-1} of CO_2 and is considered to be the major culprit in enhancing atmospheric CO_2 concentrations. With increase in population, especially of under-developed countries and the ambition of improving standard of living (fossil fuel consumption per capita being used as a routine

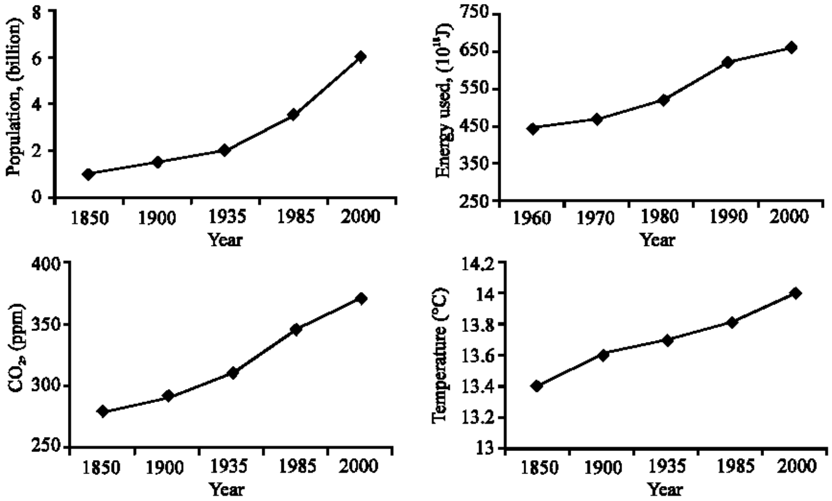

Fig. 1: Recent trends in global temperature, atmospheric CO_2 concentration, human population and energy consumption

parameter), there is every likelihood that CO_2 concentration of the atmosphere will continue rising. Thus in the foreseeable future with consistent population growth and drive towards higher standards of living, an increase in CO_2 concentration would appear inevitable. According to King *et al.*[5], without Devine intervention, the concentration of CO_2 is likely to double during the present century, especially if the current pace of development continues, finding alternative ways of fuel/energy not withstanding.

In contradiction to afore-mentioned, however, there is an increasing tendency for fossil fuel-driven CO_2 emissions to falter with time due to increased awareness about environmental issues and hike in fossil fuel price leading to economizing on use. Already, such tendency is reported to exist in developed countries (Fig. 2), while the developing countries are on the path of increasing use of fossil fuels and hence contributing more to the CO_2[1]. According to these authors, the world CO_2 emissions from fossil fuel consumption in 2001 were only slightly higher than in 2000 (<1%) although since 1990 world CO_2 emissions increased by about 9%. Major reduction comes from developed countries who have adopted efficient technologies vis-à-vis cuts in the use of fossil fuel due to economic reasons. In addition, emission trends of many countries seem to have been influenced by the Kyoto protocol. Those of China seem to be most influenced. On the other hand, China and India with the high specific CO_2 emission per primary energy unit still have a huge potential for further improvements in energy efficiency. Thus fossil fuels may not be a major cause of elevated atmospheric CO_2 in the long run.

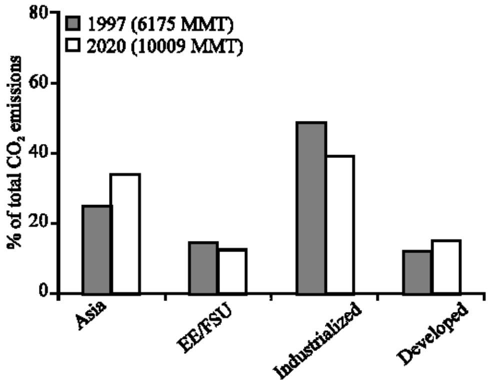

Fig. 2: Measured (1997) and predicted (2002) contribution of different regions to atmospheric CO_2

Atmospheric CO_2 and agriculture: In spite of the significant contribution of fossil fuels towards increased CO_2 levels in the atmosphere, agriculture (including forests) is one of the main sources/sinks of this gas. It will continue to play a major role in affecting the atmospheric CO_2 balance in view of the increasing human needs of food, fiber and wood. However, the aspect often overlooked with reference to global warming is the flux of CO_2 and changes over time from vegetated land (from soil and vegetation). Indeed soil represents the largest reservoir of organic C that is estimated at 1500 pg to a depth of one meter. Hence fluxes between soil organic C and the atmosphere are important, the former showing a depletion with time unless argumented with organic amendments at regular intervals. However, the role of organic matter in elevating CO_2 concentrations at the leaf level and thus plants' photosynthetic efficiency has seldom been considered. This is important as CO_2 efflux of 727 mg m^{-2} will be sufficient to double its concentration in a cubic meter of the atmosphere and sufficient too cause significant changes in plant productivity. Positive effect of doubling of CO_2 on crop and ecosystem productivity at different organizational levels is well documented[6-15]. The calculation just mentioned is based on the fact that i) atmospheric concentration of CO_2 is approximately 0.037% at present and ii) one m^3 (1000 L) of the atmosphere over 1 m^2 of land will contain 370 mL of CO_2, 727 mg CO_2, or 231 mg CO_2-C. A good body of literature suggests fluxes of CO_2 from soil much greater than required to double the concentration at least at the plant canopy level. Huntjens[16] reported an efflux of 220 mg CO_2-C m^{-2} h^{-1} (5280 mg m^{-2} day^{-1}) from pasture soil profiles; efflux from arable soil being 1/3rd of this. Using ^{14}C-labelled plant residues and components, Azam *et al.*[17] showed that 50% of the C applied as glucose, cellulose and wheat straw was respired as CO_2 within a week of incubation, while an efflux of 3-22 g m^{-2} day^{-1} from different forest communities has been reported[18]. Similarly, CO_2 efflux of 2.3 to 14.8 g m^{-2} day^{-1} has been reported[19]. Many other studies also show substantial efflux to the atmosphere of CO_2 from soil[20-27].

The overall global flux of CO_2 from soil-plant system is estimated at approximately 220×10^9 tons per annum[28]; unplanted land also releases about 220×10^9 tons CO_2 making a total flux from land equivalent to 440×10^9 tons $year^{-1}$. However, the figures for CO_2 flux from vegetation do not appear commensurate with other estimates. For example, recalculation of data by Buchmann and Schulze[29] shows alarmingly high values for CO_2 emissions from different terrestrial ecosystems. They have reported a flux of 1.7-85 μmol CO_2 m^{-2} sec^{-1} from different types of plantations (agricultural as well as non-agricultural). This is equivalent to 22-1100 tons ha^{-1} $year^{-1}$. Taking statistics on the website of World Food Organization (FAO) as valid, the vegetation covers 13,000 million ha[30]. Hence, data provided by Buchmann and Schulze[29] would suggest a global CO_2 flux of 286×10^9-14.3×10^{12} million tons $year^{-1}$.

Coming back to CO_2 flux from agricultural lands, the estimated acreage stands at 5012 million ha and has not shown a major increase in the past 4 decades with negligible change in total land use and a significant increase in the area under permanent crops/pastures; irrigated area also increased by >40%[30] (Fig. 4). In comparison to land utilization for agricultural activity, the production of major crops has shown an average increase of 60% over the past 4 decades due to improvements in agricultural practices (Fig. 4). This increased production has resulted mainly from improved crop husbandry including the use of chemical fertilizers which sowed >60% increase in the past 4 decades as did the total crop production.

Statistics of annual CO_2 flux for agricultural areas are generally missing[29]. However, the share of the agricultural land to the total CO_2 flux can be calculated as 1/3rd of the total flux of 220×10^9 tons $year^{-1}$ i.e., 73×10^9 tons $year^{-1}$. This calculation will be based on the area and not the agricultural production. It is understandable that with increase in dry matter accumulation and hence agricultural productivity, CO_2 will increase from both soil and the plants. It is generally considered valid that 30-50% of the photosynthetic carbon gathered by annual crops during their life time is

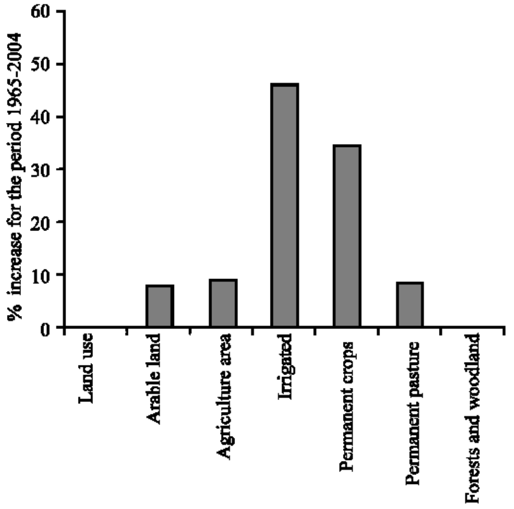

Fig. 3: Changes in land utilization during the past 4 decades

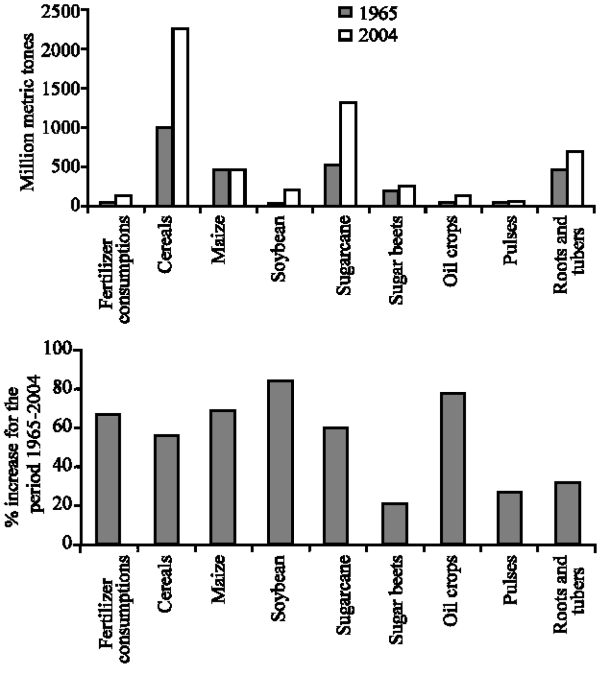

Fig. 4: Consumption of fertilizer and production of some major crops in 1965 compared to that in 2004 and the percent change during this period

translocated below-ground as rhizodeposits[31,32]. In fact, almost all organic C found in soil is primarily plant-derived in the form of root/shoot residues and root exudates[33,34]. A significant proportion of the rhizodeposits is lost through rhizospheric respiration that may represent 51 to 89% of the total CO$_2$ efflux from soil; half of this coming from root respiration[35]. Of the total C translocated below-ground, 7-13% is ultimately found in roots, 2-5% exuded and 7-14% used up in root respiration for the maintenance, root growth and ion uptake[33,34].

As mentioned earlier, agricultural productivity has increased by at least 60% over the past 4 decades. This would have certainly led to increase in rhizodeposition and thus the return of CO$_2$ into the atmosphere. However, increased rhizodeposition also means sequestration of greater amounts of CO$_2$ into soil organic matter for release back into the environment at variable pace depending upon the chemistry of the new products. It is a matter of satisfaction for the environmentalists that plant productivity increases at elevated levels of CO$_2$. Indeed, the positive response of plants to elevated CO$_2$ is present, to a lesser or greater extent in all types of vegetation[36] and is observed at plant as well as ecosystem level. A review of 430 individual experiments showed that the productivity of most herbaceous plants rose by *ca* 30% in response to doubling of CO$_2$[37]. An analysis of 55 experiments revealed an increase of >200% in productivity at additional 600 ppm CO$_2$ under water limiting conditions[38]. The arctic sedge *(Eriophorum vaginatum)* is among the few studied communities that did not maintain higher assimilation rates at elevated CO$_2$[14]. The effect of CO$_2$ has been much more pronounced when environmental factors are severely affecting the growth and development of plants[39]. Under conditions that limit ecosystem productivity, elevated CO$_2$ has been reported to help plants overcome some of the restrictions[40,41]. Hence, the vegetation and its products are not only a source but substantial sink for CO$_2$. Increased plant activity not only leads to CO$_2$ sequestration but may have implications to the rate of decomposition relatively recalcitrant native soil organic matter. This will certainly tilt the balance in favour of net efflux of CO$_2$ into the atmosphere. Priming effect on native soil organic matter of roots and root-derived organic materials is quite well established that is achieved mainly through enhanced microbial activity[42,43], while under controlled laboratory conditions presence of easily oxidizable C compounds is reported to facilitate the decomposition of complex materials[44-48].

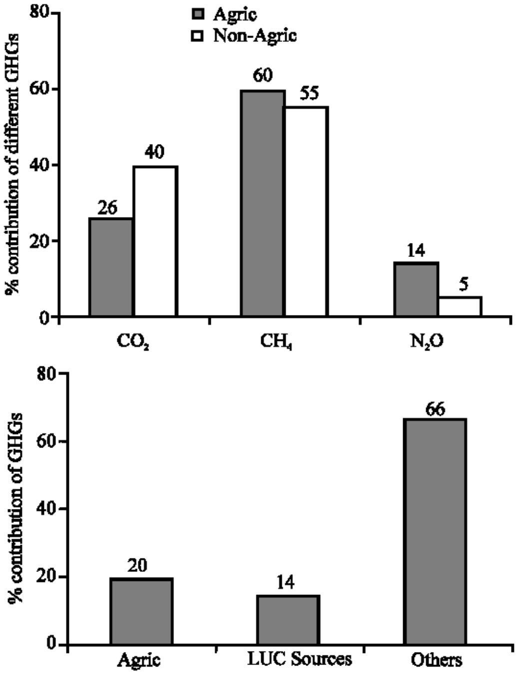

Fig. 5: Contribution of agriculture an non-agriculture sources to greenhouse gases (GHGs); LUC land utilization cange

The contribution of agriculture to the total GHGs is estimated at 20%, while 14% comes from land use changes and the remaining 66% from other sources (Fig. 5, lower part). The upper part of Figure 5 shows percent distribution of the total GHGs in CO$_2$, CH$_4$ and N$_2$O in comparison to that from other sources. As can be seen, CH$_4$ and N$_2$O are more important compared to CO$_2$ as far as agricultural gas emissions are concerned. However, the significance of CO$_2$ originating from agriculture becomes evident when compared with CO$_2$ emissions from fossil fuel burning. Annual global flux of CO$_2$ from terrestrial systems being 220×10^9 tons annum^{-1}[28] as stated earlier, half of this could be considered to come from agricultural and pasture lands i.e., 110×10^9 which is several time higher than that released by fossil fuel burning i.e., ca 15×10^9 tons year^{-1}. However, the efflux of CO$_2$ into the atmosphere and sequestration by the vegetation is generally considered to be in equilibrium. Thus agriculture may not be a major contributor to the elevated levels of CO$_2$ presently encountered.

Agriculture and atmospheric Water Vapour (WV): The discussion presented above suggests that agriculture may not be a significant contributor to global warming through CO$_2$ although the other two commonly recognized GHGs i.e., CH$_4$ and N$_2$O enter into the atmosphere mainly through agricultural activity. In any case, these GHGs have only 5% contribution to global warming, whereas the remaining 95% is due to WV that comprises 1-2% of the atmosphere. Indeed, water vapour has an observable major greenhouse effect which is far larger (roughly 54 times) than the CO_2 effect. It is a common observation that cloudy days are warmer than the clear days. The significance of WV is also obvious from the fact that contribution of human activity to greenhouse effect is 0.28% if water vapour is taken into account and 5.53% if not[2]. This point is crucial to the debate over global warming whether or not water vapour is counted in an analysis. But it does make the figures of human contribution either negligible or significant. Figure 6 gives an account of the significance of different GHGs to the Greenhouse Effect (GHE) with and without WV being considered and partitioning between natural and anthropogenic origin. Of the total WV, 99.99% is of natural origin as is the greater proportion of other gases except for CFCs which are mostly anthropogenic. However, the role of vegetation (agriculture in particular) in augmenting, albeit temporarily, to the atmospheric WV is seldom considered. This happened as if agriculture is not anthropogenic and only CO_2, CH_4 and N_2O are the GHGs resulting from this activity.

Evapotranspiration (ET) is a critical hydrological link between the earth's surface and the atmosphere. It is therefore important for issues involving many aspects of climate change and ecosystem responses. Through ET, the plants may make a significant contribution to the atmospheric WV, while maximum yields are related to maximum ET. Any increase in crop yields is commensurate with increase in water use and ET. Over the past 4 decades crop yields have increased by at least 60% and a similar would be true for ET. However, most studies neglect or oversimplify the feedback between the vegetated surface and the lower atmosphere.

For every ton of produce an estimated 2000 tons of water is required i.e., 2000 L of water per kg of the produce[30]. The entire amount of this water ultimately finds its way into the atmosphere during the life of the crop plants. Presently, the annual production of major agricultural crops roughly stands at 5671 million tons $year^{-1}$ as compared to 2545 million tons in 1965 (Fig. 4) according to the statistics given on the website of Food and Agriculture Organization of the United Nations. Even these estimates are highly conservative as it takes into account only the major crops life cycle of which is mostly less than 6 months. In any case, the increase in crop yields would lead to a concomitant rise in WV over the cropped area and into the deeper atmosphere on the long term. Assuming 1-2% atmosphere being occupied by WV[47], the volume of the latter comes to ca $37\text{-}74\times10^{15}$ m^3 ($30\text{-}60\times10^{12}$ tons). Considering the aforementioned relationship of water used to biomass produced i.e., 2000:1, 11.34×10^{12} tons of H_2O will be lost to the environment to obtain 5671 million tons of produce in the year 2004. Add to this the fact that the crop production is computed as a sum of some important crops none of which takes more than 6 months to mature. Hence, the amount of water lost to the atmosphere will be at least twice of that just mentioned and will come to about 22.68×10^{12} tons $year^{-1}$. This is a tremendous amount with a potential to elevate atmospheric WV content of $30\text{-}60\times10^{12}$ by approximately 0.13% daily.

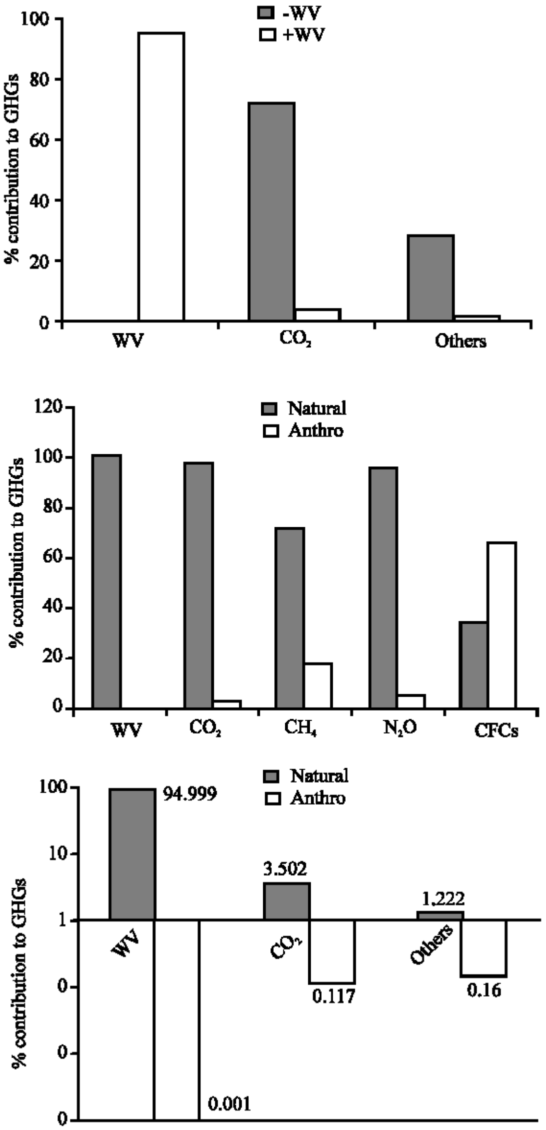

Fig. 6: Natural and anthropogenic contribution to GHGs and the significance of water vapour (WV)

In summary, the calculations given in the preceding paragraph suggest an astonishing role of agricultural crops in elevating the level of atmospheric WV by at least 38-76% every year at the present levels of crop production. This contribution was 17-34% in 1965 based on production levels of 2545 million tons mentioned above. Since, land under agricultural crops has not increased significantly (Fig. 4) any increase is due to improved crop husbandry. This would suggest that present-day modernized agriculture is a major factor contributing to the elevated levels of atmospheric WV. Any increase in agricultural productivity means further additions to atmospheric WV as evapotranspiration (ET) flux bears a close relationship with carbon assimilation during the process of photosynthesis[29].

The above account becomes a major concern when Global Warming Potential (GWP) of WV is taken into account. Interestingly, however, human activities are not believed to directly affect the average global concentration of WV[49], while most of the global warming studies simply do not include WV as the GHG. It is pertinent to suggest therefore that WV generated from agricultural activity must be considered as an important but so far unavoidable factor in global warming. Hence, strategies need to be evolved to curtail the loss of water through ET. This could possibly be accomplished through breeding crop types that have improved water use efficiency.

CONCLUSIONS

In order to ensure food security for the increasing human population, agricultural activity/productivity is bound to increase with a concomitant rise in evapotranspiration (ET). The present analysis suggests that vegetation and croplands are important sources of GHGs, particularly of WV. The impact of agriculture on global warming may be more pronounced through ET than the release of CO_2, CH_4 and N_2O. While N_2O emissions can be curtailed by adopting appropriate fertilizer management practices and concerns about CO_2 will be negligible due to its simultaneous sequestration in the vegetation, WV released through ET will be a significant GHG resulting from agricultural activity but on which no controls can easily be applied. Evolution of crop varieties with higher water use efficiency will be a promising option not only to curtail the losses of water through ET (thus curtailing global warming) but to harvest good crops in the wake of diminishing water resources in the years to come.

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