***Pak. J. Bot.*, 55(4): 1449-1458, 2023.** **DOI: http://dx.doi.org/10.30848/PJB2023-4(20)**

SPATIO-TEMPORAL DYNAMICS OF GREENHOUSE GAS EMISSIONS FROM SOIL IN FOREST ECOSYSTEMS OF PAKISTAN

SABEEQA USMAN MALIK[1], MUHAMMAD IRFAN ASHRAF[1*] AND MUHAMMAD ARIF GOHEER[2]

[1]Department of Forestry and Range Management, PMAS Arid Agriculture University, Rawalpindi 46300 Pakistan
[2]PSO/Head Agriculture, Forestry & Land Use Section, Global Change Impact Studies Center,
Ministry of Climate Change, Government of Pakistan, Islamabad, Pakistan.
[*]Corresponding author: email: drirfancanada@gmail.com ; irfan.ashraf@unb.ca

Abstract

Intergovernmental Panel on Climate Change (IPCC) in its sixth assessment report (AR-6) has documented that the atmosphere, ocean, and land have been warmed at an unprecedented rate as per history of last 2000 years. Greenhouse gas (GHG) emissions from agriculture and forest soils account for 24% of the total global emissions. Soil processes directly contribute to climate change through the production and consumption of carbon dioxide (CO_2), methane (CH_4) and nitrous Oxide (N_2O). Because of huge spatial and temporal variability in the soil-atmosphere exchange of GHGs, the measurement of prevailing concentrations and prediction are still difficult. Under different forest types, soil responds in a dissimilar fashion under varying climatic conditions. This research endeavor was pursued to estimate GHG accumulations from soil under scrub, subtropical pine and moist temperate forests. This study is of unique scientific efforts and features in which empirical data of the soil GHG emissions was gathered based on field observations. The present study apprehended forest diversity and temporal variations using a static chamber and photoacoustic spectroscopy to estimate GHG accumulations from soil. Seasonal variations strongly influenced CO_2 emissions in three forest types, while N_2O accumulation was not influenced by seasonal variations. In the winter season, the GHG accumulation decreased due to reduced microbial and root respiration. Methane was not detected in any of the forest types investigated in this study. Our results showed that soil under moist temperate forests produced more CO_2 in summer as compared to that in the other forest types. The subtropical chir pine forest has the highest N_2O accumulation in both summer and winter seasons. The outcomes of the research will be useful for developing national GHG inventory as well as Forest Reference Emission Levels (FREL) for REDD+ implementation under the Paris Agreement. Further, the data produced in this study may be helpful in carbon trading under Kyoto Protocol. The present approximations of GHGs will aid in predicting the future climate trends.

Key words: Gas analyzer; GHG emissions; Emission trends; Forest soils; Soil emissions; Static chamber.

Introduction

Greenhouse gases (GHGs) entrap electromagnetic radiations in the atmosphere and warm the earth. The infrared radiations emitting from the earth surface (as a black body) are caught by GHGs in the atmosphere. The capturing of radiations is regulated by the geographic conditions, seasonal variations as well as type and quantity of the GHG. This phenomenon of natural greenhouse effect composes a comfortable habitat for living organisms by maintaining suitable temperature of the earth. Global average temperature is around 14°C; it would have been around -19°C without this natural greenhouse effect (Kweku *et al.*, 2017). The increasing GHG concentrations due to anthropogenic activities are disturbing the global energy balance through climate forcing or radiative forcing. It has direct influence on regional and global climate that is affecting agriculture and forest production, human health and national economy (Kweku *et al.*, 2017; Latake *et al.*, 2015). The carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most important GHGs accountable for change and variation in climate forcing. The most crucial one is CO_2 for its large quantity in the atmosphere compared to other GHGs. However, CH_4 and N_2O are more efficient in trapping radiation than that of CO_2. The highly influencing nature of CH_4 and N_2O makes it more hazardous even at lower concentrations compared to CO_2. Methane and N_2O, for absorbing infrared rays, have higher global warming potential than CO_2. In comparison to CO_2, CH_4 has 28 times higher and N_2O has 265 times higher global warming potential (IPCC, 2013).

Global, annual emissions due to anthropogenic activities exceeded up to 36.2 Gt during the year 2016 compared to 22.3 Gt in 1990 because of the emissions from cement industry and burning fossil fuels (Anon., 2018). Another important anthropogenic source emitting GHGs is agriculture farming and land-use sector that accounts for 4-5 Gt of GHG emissions every year worldwide (Anon., 2018). During the past decade (2000-2010), the GHG emissions were increased by 17% and on an average 60 Mt CO_2 equivalent of GHGs were emitted every year globally (Benbi, 2013).

Internationally, leading natural sources of CO_2 include oceans (330 Pg), plant and animal respiration (220 Pg) and soil respiration (220 Pg) (IPCC, 2013; Gerlach, 2013; USGS, 2014). The natural sources of CH_4 emissions include wetlands (177-284 Tg), termites (20-29 Tg), oceans (4-15 Tg) and wild fires (2-5 Tg) (IPCC, 2013; Van-Amstel, 2012). Almost 6.6 million tons of N_2O were released from the soil under forests and other natural vegetation that account for almost 60 % of the total natural emissions of the world (IPCC, 2007). However, natural sources are assumed to be in a balance for their emission and storage potential of GHGs. Greenhouse gas production due to human activities is believed to be the primary reason for altering the global energy balance and resultant global warming (Hensen *et al.*, 2013). Anthropogenic activities include deforestation, combustion of fossil fuel and changes in land-use pattern.

The conversion of forests to agricultural lands resulted in reduction of 20-50% of stored carbon from the upper one-meter earth layer (Berihu *et al.*, 2017). Carbon dioxide, CH_4 and N_2O accounts for 76 %, 16 % and 6 % share in total GHGs, respectively (Oliver *et al.*, 2017). Sectoral share of GHGs in the world is shown in Fig. 1.

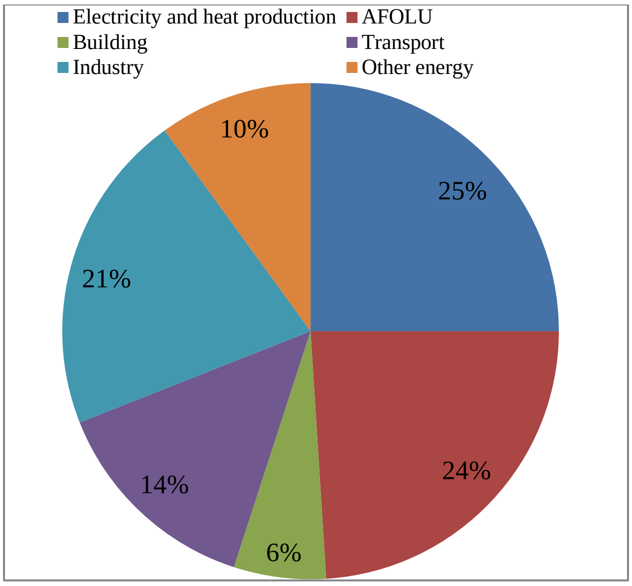


Fig. 1. Global share of GHG emissions for different sectors.

A study based on the data of 40 years (1970-2010) revealed that approximately 90% GHG emissions in the Least Developed Countries (LDCs) are produced by agriculture, forestry and other land-uses (AFOLU). An annual increase of 0.6% has been witnessed. The primary activities within AFOLU for the LDCs comprised sustenance agricultural, livestock rearing and use of timber as a fuel for domestic heating and cooking (Golub *et al.*, 2009; Dauvergne & Neville, 2010; Erb, 2012). The emissions of CO_2, CH_4 and N_2O from AFOLU sector were 13%, 44% and 82% respectively as per global emissions recorded during 2007-2016. It is also evident that changes in land-use, especially conversion of forest lands to agriculture and urban lands affect the overall GHGs balance on the earth (Pörtner *et al.*, 2019).

Soil is both a source and a sink of GHGs. The extent of GHG emissions from soil is based on management and land-use strategy. Physicochemical properties of soil are imperative to its role as source and sink (Smith *et al.*, 2018). These influence its storage ability for the GHGs. The fundamental processes that control GHG emissions from soil include soil microbial activity, soil decomposition, respiration by plant roots, and respiration by soil fauna and fungi (Gougoulias *et al.*, 2014). The contribution of root respiration is about 50% of the total respiration but it may deviate to 95% subject to season and vegetation type (Zhang *et al.*, 2019). Under anaerobic conditions, methanogenesis results in the production of CH_4 from soil which is utilized by methanotrophic microbes for their metabolic activities (Serrano-Silva *et al.*, 2014). The temperature, moisture, nutrient status, texture, structure and pH of the soil are driving factors for the emissions of GHGs from soil and are thus the core cause of global warming. A recent estimate depicts that global soil emissions account for 98 Pg C year^{-1} which is considerably higher than earlier statistics of 68-77 Pg C year^{-1} (Bahn *et al.*, 2010). Therefore, the amount of GHGs emitted from the soil needs to be well quantified.

It has been registered that forests cover 31% of the earth surface and contain 77% of the above ground terrestrial carbon (Keenan *et al.*, 2015). Globally, total carbon stock in forests is estimated to be 861 Gt out of which the share of living biomass, litter and soil is 363 Gt, 116 Gt and 383 Gt, respectively (Ciais *et al.*, 2014; Pan *et al.*, 2011). Terrestrial vegetation plays a significant role in carbon cycle by capturing 123 Gt carbons annually worldwide. Around 119 Gt carbon elements are returned to the atmosphere by respiration (Ciais *et al.*, 2014). On the other side, natural ecosystems under forest lands produce 3.37-6.60 Tg of N_2O per annum globally with tropical rain forests being the single largest natural source of it (Zhuang *et al.*, 2012). Although more carbon is released to the atmosphere from forests as compared to the collective anthropogenic emissions but most of this carbon is recaptured. This is how forests act as carbon sink and play a central role in mitigating climate change (Brandon, 2014).

One can note that forest vegetation composition, biodiversity and regeneration patterns are strongly influenced by spatial as well as temporal factors. Spatial factors include environmental features, aspects, slope, elevation and distance. The change in species composition is observed along with elevation gradient. Altitudinal change directly influences humidity and temperature as well as soil characteristics. Globally, the highest plant biodiversity is found at middle elevation points (Körner, 2007). Slope and aspect influence vegetation patterns by altering duration of day light, temperature and humidity (Virtanen *et al.*, 2010). Temporal variations significantly influence GHG emissions and are largely driven by seasonal fluctuations. The climate with a specific seasonal pattern results in temporal variations in forest growth, survival and productivity. Similarly, climate also directly influences biotic and abiotic processes and eventually GHG emissions from the soil. Temporal variations like day and night and seasonal sequence strongly influence GHG's emission. Temporal data is unidirectional which can be used to predict the future pattern of the emissions.

Pakistan has been ranked at 8th among adversely affected countries of the world due to climate change. The country has lost 0.52% per unit of its Gross Domestic Product (GDP) with an economic loss of USD 3792.52 million due to climate change during 1999 to 2018 (Eckstein *et al.*, 2019; Global Climate Risk Index, 2020). A steady increase in GHG emissions is expected in Pakistan, it was 347 Mt in 2011 and increased up to 557 Mt by 2020 and anticipated to be increased to 1046, 2156 and 4621 Mt by 2030, 2040 and 2050, respectively if present emission levels are continued (Abas *et al.*, 2017).

Most scientists believe that global change is an outcome of human expansion of greenhouse effect. Humans will be the most affected creature on this planet. Climate change can be tackled by increasing number of trees in order to enhance carbon sinks to reduce GHG's concentration in the atmosphere.

The measurement of GHG emissions from various sectors is important because by knowing current emission tendencies, predictions about the future trends of climate change can be made with more confidence and reliability. This reliable information is the key to right strategy for climate change mitigation. The GHG emission data is also required for national GHG inventory for REDD+ implementation under Paris Agreement of 2016. Under Paris Agreement Article-13, each country is bound to provide its GHG emission data on periodic basis. Greenhouse gas inventory of economic sectors conclude Nationally Determined Contributions (NDC) of each country. This study will contribute towards national economy by adding accurate field based information of major forest types in the database of forest reference emission levels (FREL) and forest reference level (FRL) which is basic requirement for international carbon trading. Furthermore, the soil emission related data is also useful in effective management of forests in the very context of climate change. Besides providing the soil emission data, a standard measurement protocol under regional forest and climatic conditions was developed for extensive application and a guide for the future studies.

The objectives of the study were to explore spatial patterns of GHG emissions and temporal dynamics, along with quantification of soil GHG emissions in forest ecosystems across subtropical and temperate regions of Pakistan.

Materials and Methods

Description of the study area: Pakistan is 33rd largest country by area in the world. It lies between 61° and 75° East longitudes and 24° and 37° North latitudes (USGS, 2021). Location of the study area is shown in Fig. 2. The highly diverse landscape of the country supports great diversity of flora and fauna. Pakistan is a forest poor country but still has best representation of diverse forest types due to assorted geography and topography. Out of total area of Pakistan only 5.1% (4.479 million hectares) is under forest cover (Keenan *et al*., 2015). The major reason behind low forest cover is the arid and semiarid climatic conditions under 70-80% area of the country. This unfavorable climate encompassing low precipitation hampers tree growth and survival in Pakistan (Keenan *et al*., 2015). Forests of Pakistan spreads from arid and tropical zones of Sindh and Baluchistan to cold deserts and snow fields in north; from tropical dry deciduous forests in the Himalayan region to dry temperate forests in inner Himalayas and from the riverine and swamp forests of the Indus and its branches to the littoral forests (Roberts, 1997). Share of different forest types in total forest area of the country is presented in Fig. 3.

This study has focused on subtropical and moist temperate forests of Pakistan. The study area spreads over the administrative districts of Chakwal, Islamabad (federal capital), Rawalpindi (tehsil Murree only) and Abbottabad.

Moist temperate forests (MTF) are situated in district Abbottabad whereas subtropical forests are spreading over districts Rawalpindi, Chakwal and Islamabad. Subtropical forests are further classified into two forest types: scrub and subtropical pine forests (SPF). The three forest types under study comprised of almost 75% forest cover of Pakistan.

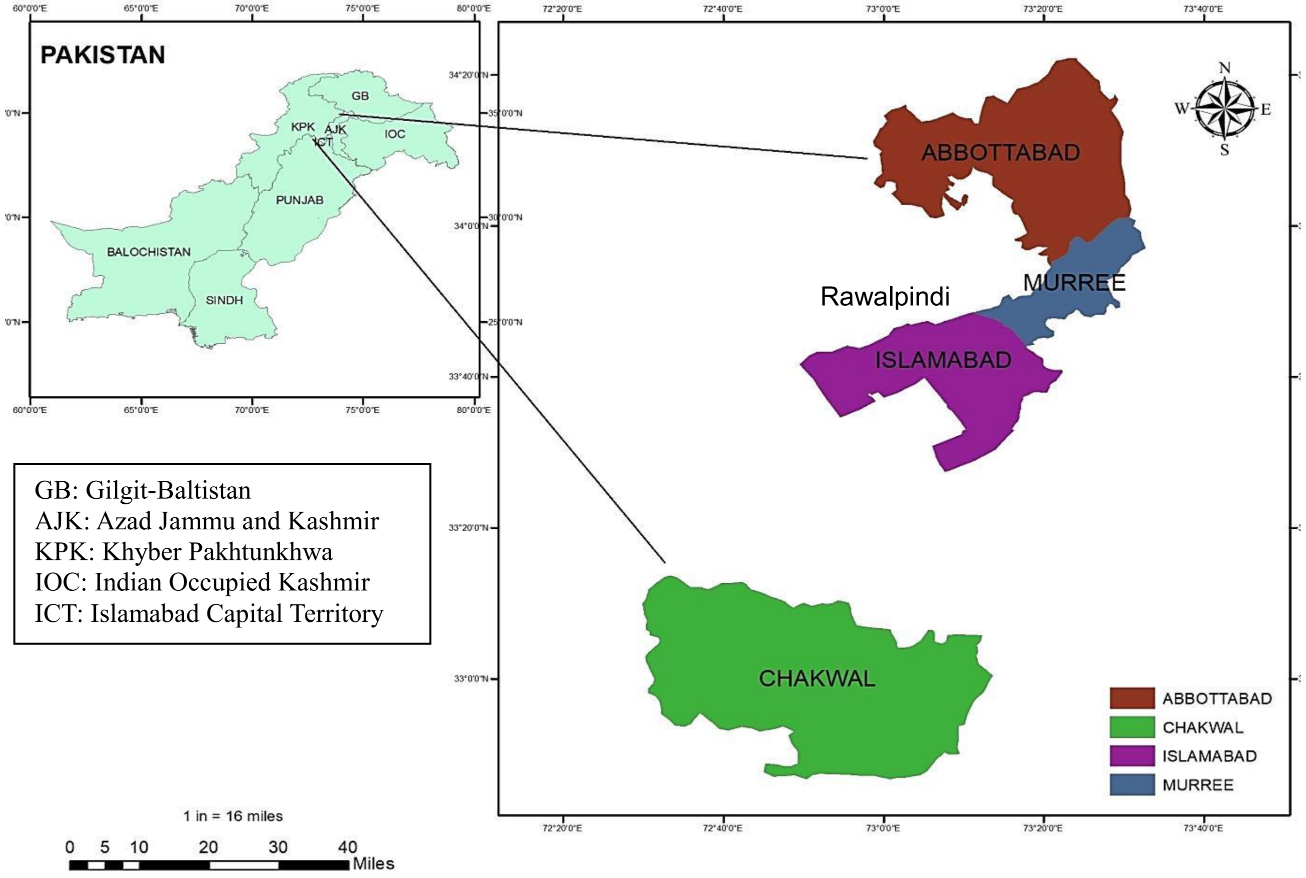


Fig. 2. Location of the study area in Pakistan.

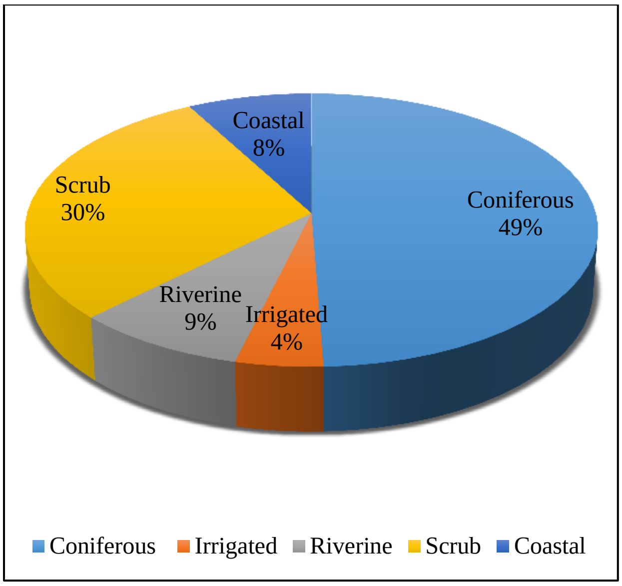


Fig. 3. Forest cover of Pakistan by types. (Adopted from Bukhari *et al*., 2012).

The climatic, geographic and vegetative attributes of the study area are summarized in Table 1.

Stratification of the study area: A strong scientific sampling strategy is considered necessary to collect best representative data in the field studies. The stratified random sampling is such a statistical technique as is used to acquire the best representation of the study area. The stratification process included segmenting of the large population (forest types) into strata or subgroups. The forest stratification was based on topographic attributes which included elevation and slope because these factors control distribution of tree species as well as their existence and survival (Sharma *et al*., 2016; Joseph *et al*., 2012; Zhao *et al*., 2013; Liu *et al*., 2018).

Sampling strategy and data collection: The information regarding topographic features was extracted from Digital Elevation Model (DEM) using Geographic Information System (GIS) software ArcGIS 10.3 and 30m resolution satellite imagery in Google Earth was used to recognize forest types. Initially, thematic maps of slope and elevation were developed. The strata within each forest type were developed by integrating and classifying slope and elevation data (Liu *et al*., 2018). Twenty eight observation points were randomly selected in four strata within each forest type. The composition of tree species and forest density were recognized by visual elucidation while selecting sampling sites. The data regarding GHG concentration in all three forest types was recorded for summer and winter seasons separately. Fig. 4 illustrates complete data collection process. After selecting sites, point elevation and geographical coordinates were recorded with the help of GPS. The GHG accumulation over time was measured by portable gas analyzer employing closed static chamber technique. This technique has gained wide acceptability due to its efficiency, portability and cost effectiveness (Ahmad *et al*., 2020; Rochette & Eriksen-Hamel, 2008; Rochette & McGinn, 2005; Mosier, 1994).

Closed static chamber: operating principle, design and dimensions: The closed static chamber was designed to restrict gaseous exchange between soil emissions and atmospheric gases (Denmead, 2008). The chamber used in the study was made up of iron. In order to make it durable and solid, it was painted from outside and inside to avoid any chemical reaction with the gases and external heating by solar radiations in the atmosphere. Portable gas analyzer with a vent on the top of the chamber was used to record GHG emissions. The dimensions of chambers used in the study were length: 0.6096 m, width: 0.6096 m and height: 0.305 m. Therefore, area and volume of the chamber were 0.3716 m^2 and 0.1133 m^3, respectively.

Chamber placement and sampling time: The GHG emissions were recorded during 9-11 am as this interval indicates average accumulation of the day (Rochette, 2011). The chamber was inserted in the soil by 8 cm deep to get a proper anchor. Four readings at the time interval of 0, 10, 20, 30 minutes were taken from each sampling site. The GHG accumulation at each sampling site was replicated three times. The seasons have critical influence on accumulation of GHGs due to variation in temperature and moisture. The seasonal variations were assimilated by recording GHGs in summer (May-July) and winter (December-February) seasons (Denmead, 2008).

Photo-acoustic spectroscopy method: Photo acoustic spectroscopy (PAS) based portable gas analyzer technique has recently gained a momentum due to its efficiency and cost effectiveness. The principle of PAS is that GHGs captivate light at a precise wavelength in the ultraviolet spectrum. According to Beer-Lambert law, this absorption in the gas analyzers generates light which is converted into a signal and recorded by a sensor (Darenova, 2014; Swinehart, 1962).

Table 1. Climatic, geographic and vegetative attributes of the study area.

Sr.no.	District	Elevation (m)	Temperature (°C)	Precipitation (mm)	Dominant tree species
1.	Chakwal	560 -700	4-40	350-500	*Acacia modesta*, *Olea ferruginea*
2.	Rawalpindi	300-2790	3.2-39.4	380-1710	*Acacia modesta*, *Olea ferruginea, Pinus roxburghii, Quercus incana*
3.	Islamabad	450-1600	13-40	380-510	*Acacia modesta*, *Olea ferruginea*
4.	Abbottabad	1256-4117	-2.01-23.45	508-1743	*Cedrus deodara, Pinus wallichiana, Picea smithiana, Abies pindrow*

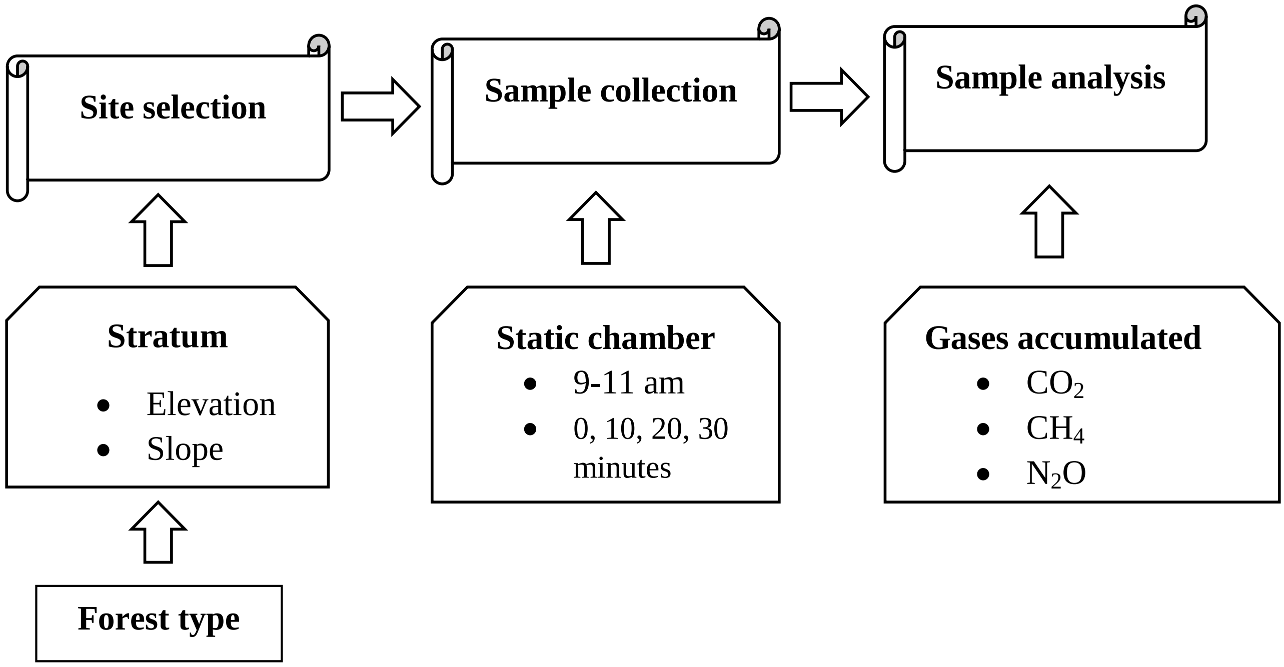


Fig. 4. Flow diagram of GHG profiling process.

Data analysis: The GHG accumulation of CO_2 and N_2O for three forest types were plotted overtime (minutes) by season in order to identify emission tendencies. The descriptive statistics of data was explored to learn about trends. The statistical difference among forest types and seasons for GHG accumulation was estimated by applying Analysis of Covariance (ANCOVA) test, which is a blend of simple regression and Analysis of Variance (ANOVA). This test is preferred in case of more than one independent categorical variable. Lack of fit statistics was also employed to check the fitness of the statistical test. This technique is used to test whether the statistical tool fits to the data or not. This test gives result only in case of suitable statistical analysis selection otherwise it does not estimate data. Data analysis was made using IBM SPSS V28 and Microsoft Excel.

Results

Stratification of the study area: The vegetation of district Islamabad and district Chakwal (Punjab) is the true representative of scrub forests. These districts were further stratified on the basis of topographic factors i.e. elevation and slope as shown in Table 2. The elevation and slope information retrieved from DEM of the district Islamabad and district Chakwal (Punjab). Keeping in view elevation range, scrub forests were further categorized into two elevation classes (Table 2). Low elevation class was assigned to areas below 500 m while high elevation class assigned to areas greater than 500 m. Slope in the study area (scrub forests) ranged between 0-27 degrees which is relatively low as compared to other forest types. The scrub forest area was categorized into two classes of low and high slope. Lower slope class consisted of areas having slope between 0-13 degrees while high slope class was between 14-27 degrees. After slope and elevation classification, four strata were developed as shown in Table 2.

Subtropical pine forests are located in tehsil Murree, district Rawalpindi. The elevation range retrieved from DEM of tehsil Murree was between 914-1730 m which is within the range as described in conventional forest classification. It was further categorized into two elevation classes of low and high as shown in Table 3. Lower class is stretched over 914-1322 m while the high elevation class is ranged between 1323-1730 m. The slope in SPF was from medium to gentle ranging from 0-75 degrees. Slope was categorized into two classes: low and high. The lower range was between 0-35 and high slope class was between 36-75 degrees. Four strata so developed were low elevation-low slope (LeLs), low elevation-high slope (LeHs), high elevation-low slope (HeLs) and high elevation-high slope (HeHs) as shown in Table 3.

According to the conventional classification of the forests in Pakistan, MTF lies between 1670-2590 m (Champion *et al*., 1965). Forests of Nathia Gali and adjacent areas in district Abbottabad are in the category of MTF. The information retrieved from DEM of district Abbottabad indicated the elevation range of 1674-2593 m. The elevation was classified into two groups of low and high magnitude. The low class was between 1674-2134 m while the high class ranged between 2134-2593 m (Table 4). In addition to elevation classes, slope classes for the district Abbottabad were developed and slope ranged between 0-65 degrees. Strata developed on the basis of slope and elevations are presented in Table 4.

Carbon dioxide accumulation by season: The accumulation of CO_2 during summer and winter seasons is shown in Fig. 5. The emissions were recorded for 30 minutes at the interval of 10 minutes (0, 10, 20 and 30). Generally, GHG emissions in summer were higher than that of winter season. In summer season, the highest emissions were recorded in MTF while the lowest emissions were registered in SPF. However, the highest emissions were observed in scrub forests while the lowest emissions in case of SPF forests during winter season.

Table 2. Elevation and slope classes of scrub forests.

Elevation/Slope	Low (0-13°)	High (14 -27°)
Low (<500 m)	LeLs	LeHs
High (>500 m)	HeLs	HeHs

Table 3. Elevation and slope classes of subtropical pine forests.

Elevation/Slope	Low (0-35°)	High (36-75°)
Low (914-1322 m)	LeLs	LeHs
High (1323-1730 m)	HeLs	HeHs

Table 4. Elevation and slope classes of moist temperate forest.

Elevation/Slope	Low (0-38°)	High (39-65°)
Low (1674-2133 m)	LeLs	LeHs
High (2134-2593 m)	HeLs	HeHs

In scrub forests, the average CO_2 accumulation during winter season were 506.21, 576.50, 640.89 and 682.39 whereas in summer, it was 492.79, 617.79, 689.46, 761.71 ppm at the intervals of 0, 10, 20, 30 minutes respectively (Fig. 5 and Table 5). The average accumulation in SPF forests was 473.21, 505.14, 565.07, 602.32 and 489.39, 541.89, 574.46, 611.68 ppm at 10 minutes intervals (0, 10, 20 and 30 minutes) during winter and summer season respectively. Carbon dioxide accumulation in MTF during winter season was 427.89, 516.96, 583.86 and 651.64 whereas in summer season emissions were 465.46, 614.29, 711.29 and 773.75 ppm at the time interval of 0, 10, 20, 30 minutes, respectively.

Nitrous oxide accumulation by season: Nitrous oxide accumulation in three forest types during summer and winter seasons is shown in Fig. 6. In summer season, the highest N_2O emissions were recorded in SPF followed by MTF. The lowest emissions during summer were recorded in scrub forests. Accumulation of N_2O was recorded at the interval of 0, 10, 20, 30 minutes.

In scrub forest, the average accumulation during winter season was 0.20, 0.27, 0.31, 0.34 while in summer it was 0.11, 0.19, 0.29 and 0.33 ppm at the intervals of 0, 10, 20 and 30 minutes respectively.

The average N_2O accumulation in SPF during winter was 0.30, 0.37, 0.43 and 0.48 ppm whereas during summer it was 0.23, 0.34, 0.43 and 0.53 ppm at the time interval of 0, 10, 20, 30 minutes. Overall, average N_2O accumulation was higher at 30 minutes as compared to winter season.

In MTF, N_2O accumulation was 0.24, 0.28, 0.32 and 0.36 ppm during winter while in summer it was 0.22, 0.33, 0.39 and 0.45 ppm at the time intervals of 0, 10, 20, 30 minutes.

Methane accumulation: It is worth mentioning that throughout the study area CH_4 was never detected during any season (summer and winter) in any of the forests investigated in the present study.

Mean values of soil CO_2 emissions during 30 minutes from three forest types are presented in Table 5. Results indicated a significant difference in soil CO_2 emissions among all forest types as well as seasonal variations based on low *p*-value (0.016) (Table 6).

The results of lack of fit statistics were also applied to the data which showed best fit of statistical test on the data (*p*-value: 0.277). These results showed statistically significant difference among all forest types. Results of the ANCOVA are presented in Table 6.

Mean values of soil N_2O emissions during 30 minutes from three forest types are presented in Table 7. Results of ANCOVA for N_2O accumulations are shown in Table 8. The results revealed that the seasonal variations didn't have the significant influence (*p*-value) on N_2O accumulation while there was highly significant difference among forest types with a *p-value* of 0.001. Lack of fit test also showed best fit results with a *p*-value of 0.599.

Table 5. Average soil CO_2 accumulation from three forest types.

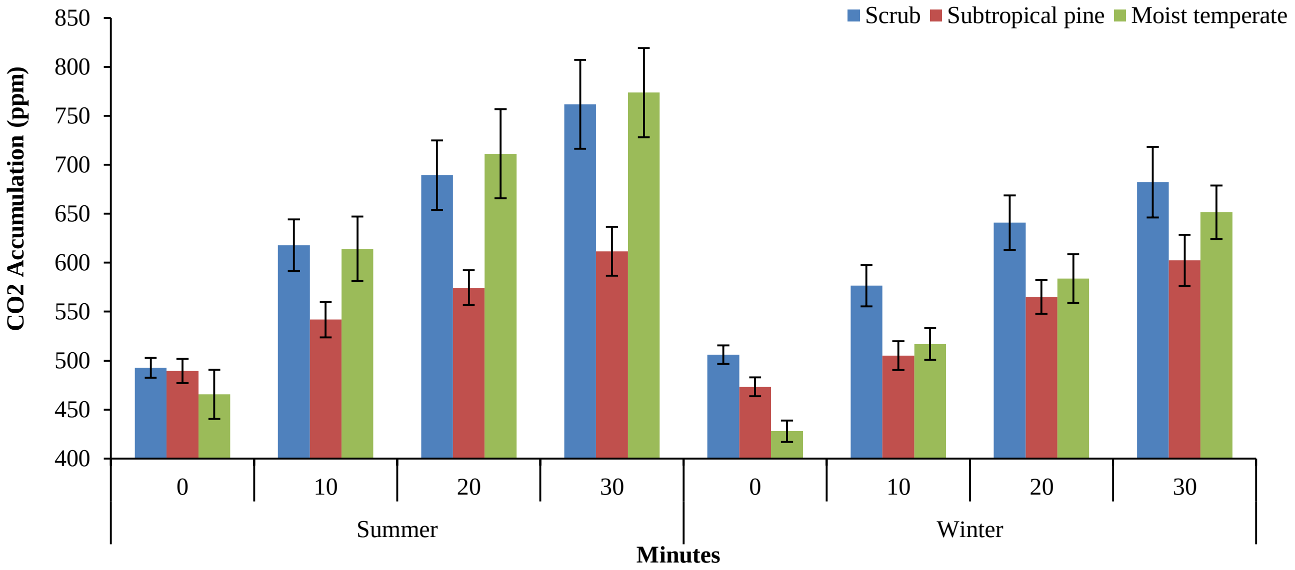
Forest type	**Average CO_2 accumulation (ppm)**							
Time (minutes)	**Summer**				**Winter**			
	0	**10**	**20**	**30**	**0**	**10**	**20**	**30**
Scrub	492.79	617.79	689.46	761.71	506.21	576.50	640.89	682.39
Subtropical pine	489.39	541.89	574.46	611.68	473.21	505.14	565.07	602.32
Moist temperate	465.46	614.29	711.29	773.75	427.89	516.96	583.86	651.64

Table 6. Results of ANCOVA for CO_2 accumulation.

Source	**Dependent variable soil CO_2**				
	Sum of squares	**df**	**Mean square**	**F**	***p*-value**
Season	207342.881	1	207342.881	5.898	0.016
Forest type	457270.155	2	228635.077	6.504	0.002
Lack of fit	90711.512	2	45355.756	1.295	0.277

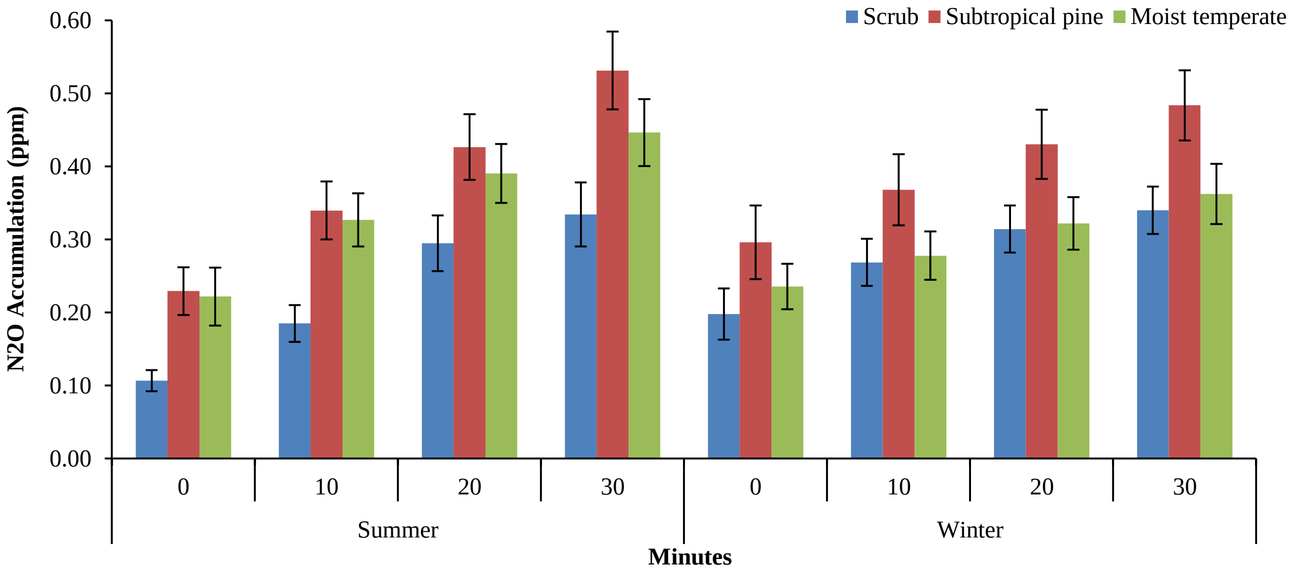
Table 7. Average soil N_2O accumulation from three forest types.

Forest type	**Average N_2O accumulation (ppm)**							
Time (minutes)	**Summer**				**Winter**			
	0	**10**	**20**	**30**	**0**	**10**	**20**	**30**
Scrub	0.11	0.19	0.29	0.33	0.20	0.27	0.31	0.34
Subtropical pine	0.23	0.34	0.43	0.53	0.30	0.37	0.43	0.48
Moist temperate	0.22	0.33	0.39	0.45	0.24	0.28	0.32	0.36



*Error bars are indicating standard error.

Fig. 5. Carbon dioxide accumulation by season from soils of three forest types.



*Error bars are indicating standard error.

Fig. 6. Nitrous oxide accumulation by season from soils of three forest types.

Table 8. Results of ANCOVA for N_2O accumulation.

Source	Dependent variable soil N_2O				
	Sum of squares	df	Mean square	F	p-value
Season	0.074	1	0.074	1.345	0.248
Forest type	0.85	2	0.413	7.472	0.001
Lack of fit	0.057	2	0.029	0.514	0.599

Discussion

United Nations Framework Convention on Climate Change (UNFCCC) requires reporting of national inventory of GHG emissions by sources and removals by sinks. In Pakistan, an initial effort was made by Global Change Impact Studies Centre (GCISC) to estimate national GHG inventory for multipurpose use. They also estimated share of different sectors of the economy in producing GHG emissions (Warlo *et al.*, 2018; GCISC, 2016). The first GHG inventory for the country was submitted to UNFCCC as a part of initial national communication of Pakistan during the period 1999-2003. This was based on IPCC 1996 guidelines for the inventory development. These estimates were limited to Tier I (basic method with lower accuracy). The emission factors used for calculation were set in global scenario rather than that of country or region specific. Advanced and more accurate methods Tier 2 and 3 cannot be adopted due to lack of national or local empirical data. A detailed assessment of different sectors of the economy was carried out in order to define Nationally Determined Contributions (NDCs). The sectors include industry, energy, agriculture and forestry. Energy sector is in the category of the highest GHG emitting sector. Total GHG emissions estimated in 1994 inventory were 181.7 million tons of CO_2 equivalents. Sector wise emissions estimates were 47.2% in Energy, 39.4% in Agriculture sector, 7.3% in Industrial Processes, 3.6% in Land Use and Forestry (LUCF) and 2.5% in Wastes.

Greenhouse gas inventory of Pakistan for the year 2014-15 was published by GCISC in 2017 [50]. UNFCCC Non-Annex I National Greenhouse Gas Inventory Software, Version 1.3.2 has been applied for the preparation of this inventory in accordance with revised 1996 IPCC Guidelines. This employed Tier-1 approach using default emission factors of revised 1996 IPCC guidelines depending on national circumstances and the availability of data of the country for emission estimation. As per inventory report, the total estimated GHG emissions for the year 2015 were 408.1 million tons of CO_2 equivalents with 45.5% share of Energy sector, 42.7% share of Agriculture, 5.4% share of Industrial Processes, 3.8% share of Waste and 2.5% share of Land-Use Change and Forestry (LUCF) sector (GCISC, 2017). This inventory provided reasonable basis for Pakistan's first NDC submitted to UNFCCC in November 2016.

Latest attempt was made in 2019 to find out recent emissions and future trends of agriculture in Pakistan (Ijaz and Goheer, 2021). According to the findings, the share of agriculture soils is 45.5% of total agricultural emissions. Generally, it is thought that vegetation areas are sinks of GHGs but in reality these are sources as well as sinks of GHGs. This study is actually an innovative attempt to generate empirical data for estimation of GHG emissions from forest soils of Pakistan.

Temporal variations (seasons) strongly influenced CO_2 emissions in all three forest types under this study. The emissions in summer season were higher than what was observed in winter (Saiz *et al.*, 2006). Winter season is considered as dormant period for biochemical and physiological activities in forests, thereby the GHG accumulation was diminished due to reduced microbial and root respiration. The same trend was observed in this research effort that the lower temperature and higher soil moisture content produced lower emissions. Soil temperature and soil moisture had integrated influence on microbial and root respiration. Generally, higher CO_2 emissions were observed in summer while lower in winter (Xu & Qi, 2001; Rey *et al.*, 2002).

It was concluded from these scientific narratives that N_2O emissions were least influenced by temporal variations. Few other studies also reported that N_2O emissions were least influenced by seasonal variations and relatively low in forest soils (Schulte-Bisping *et al.*, 2003). It is so because in the process of nitrification, moisture content remains the most influencing factor. At the level of 20% moisture, maximum nitrogen release occurs (Schulte-Bisping *et al.*, 2003). Forest typically acts as a sink of CH_4. In forest ecosystem, methanotrophic respiration in aerobic condition is the main source of CH_4 consumption in the forest. Methane was not detected in any forest type under this study. The results of this scientific research are in line with the findings of studies conducted in different forest ecosystems (Zhu *et al.*, 2014; Dalal & Allen, 2008).

Forest type and species composition have a strong influence on GHGs accumulation. A significant difference in emissions was found in all three forest types [Scrub, SPF, and MTF] (Gritsch *et al.*, 2016). Carbon dioxide accumulation in summer was the highest in MTF followed by SPF and least in scrub forests. In winter, scrub forest had the highest emission followed by MTF and SPF respectively. In MTF and SPF, the reason for huge amount of GHG emissions was higher litter and humus content due to high density, while lower emissions in winter were due to freeze thaw activities. In winter season, the highest emissions were recorded in scrub forests due to little variation in summer and winter average temperature (Ben-Noah & Friedman, 2018). Nitrous oxide accumulation trend in forests was almost similar for both seasons. The observed sequence was SPF with the highest emissions followed by MTF and scrub forests (Vanitchung *et al.*, 2011). The highest N_2O emissions were observed in SPF forests and least emissions were recorded in scrub forests. Nitrous oxide emissions were also directly related to soil nutrient content (Kesik *et al.*, 2005). The soil under SPF indicated the highest N_2O emission in current study, may be due to high soil-nitrogen content compared to other forest types investigated.

Conclusions

This research endeavour attempted to estimate GHG emissions from forest soils in Pakistan. Temporal variations (seasons) strongly influenced CO_2 emissions in scrub, SPF and MTF forests while N_2O emissions were least influenced by seasonal variations. In winter season, the emission rates were declined due to reduced microbial and root respiration. Methane gas was not detected in any of the forest types. Forest type or species composition strongly influenced GHG emissions from soil. A significant difference in GHGs accumulation was observed among scrub, SPF and MTF forests. The results showed that soil under MTF produced more CO_2 in summer than that of other two forest types whereas soil under scrub forests produced the highest CO_2 emissions in winter. Subtropical pine forests demonstrated the highest N_2O emissions in both seasons. We suggest further scientific investigations in other forest types of the region. There might be some more logical ascertainments of impact on forests across different climatic variables.

Acknowledgement

The authors are highly grateful to the undergraduate students of forestry especially Bisma, Sania, Qasim, Arif, Sher Ishaque and Waleed for their assistance in data collection and other field activities. We appreciate Dr. Anwar Ali, Director Research, Pakistan Forest Institute Peshawar and staff of Forest Mensuration Branch for generous help in hard areas/terrain during field observations and experiments. We are thankful to Dr. Abdul Saboor for editing and improving our manuscript.

References

Abas, N., A. Kalair, N. Khan and A.R. Kalair. 2017. Review of GHG emissions in Pakistan compared to SAARC countries. *Renew. and Sustain. Energy Rev.,* 80: 990-1016.

Ahmad, N., M.I. Ashraf, S.U. Malik, I. Qadir, N.A. Malik and K. Khan. 2020. Impact of Climatic and Topographic Factors on Distribution of Sub-tropical and Moist Temperate Forests in Pakistan. *Geomorphol., Relief Process. Environ.,* 26(3): 157-172.

Anonymous. 2018: *Global Carbon Project*: Supplemental data of Global Carbon Budget 2018 (Version 1.1) [Data set], Global Carbon Project, https://doi.org/10.18160/GCP-2018, 2018.

Bahn, M., M. Reichstein, E.A. Davidson, J.Grünzweig, M. Jung, M.S.Carbone and I. Janssens. 2010. Soil respiration at mean annual temperature predicts annual total across vegetation types and biomes. *Biogeosciences*, 7(7): 2147-2157.

Benbi, D.K. 2013. Greenhouse gas emissions from agricultural soils: sources and mitigation potential. *J. Crop Improv*., 27: 752-772.

Ben-Noah, I. and S.P. Friedman. 2018. Review and evaluation of root respiration and of natural and agricultural processes of soil aeration. *Vadose. Zone J.,* 17(1): 1-47.

Berihu, T., G. Girmay, M. Sebhatleab, E. Berhane, A. Zenebe and G.C. Sigua. 2017. Soil carbon and nitrogen losses following deforestation in Ethiopia. *Agron. Sustain. Dev.,* 37(1): 1-12.

Brandon, R.N. 2014. *Adaptation and Environment* (Vol. 1040). Princeton University Press, USA.

Bukhari, B.S., A. Haider and M.T. Laeeq. 2012. *Land Cover Atlas of Pakistan*. Pakistan Forest Institute Peshawar, Pakistan.

Champion, G.H., S.K. Seth and G.M. Khattak. 1965. *Forest types of Pakistan.* Pakistan Forest Institute Peshawar, Pakistan.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell and P.Thornton. 2014. Carbon and other biogeochemical cycles. In*:* (Eds.): Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley. Climate Change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK. pp. 465-570.

Dalal, R.C. and D.E. Allen. 2008. Greenhouse gas fluxes from natural ecosystems. *Aust. J. Bot*., 56(5): 369-407.

Darenova, E., M. Pavelka and M. Acosta. 2014. Diurnal deviations in the relationship between CO_2 efflux and temperature: a case study. *Catena*, 123(2014): 263-269.

Dauvergne, P. and K.J. Neville. 2010. Forests, food, and fuel in the tropics: the uneven social and ecological consequences of the emerging political economy of biofuels. *J. Peasant. Stud.*, 37(4): 631-660.

Denmead, O.T. 2008. Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere. *Plant Soil*, 309(1): 5-24.

Eckstein, D., M.L. Hutfils and M. Winges. 2019. *Global Climate Risk Index*: Who suffers most from extreme weather events. Weather-related loss events in. 2017. Available from: https://germanwatch.org/en/16046 Reeterived on 10 October 2022.

Erb, K.H. 2012. How a socio-ecological metabolism approach can help to advance our understanding of changes in land-use intensity. *Ecol. Econ*., 76: 8-14.

GCISC. 2016. *Greenhouse Gas Emission Inventory of Pakistan for the Year 2011−2012. GCISC-RR-19.* Global Change Impact Studies Centre, Ministry of Climate Change, Government of Pakistan.

GCISC. 2017. *Greenhouse Gas Emission Inventory of Pakistan for the Year 2014−2015. GCISC-RR16 20.* Global Change Impact Studies Centre, Ministry of Climate Change, Government of Pakistan.

Gerlach, T. 2011. Volcanic versus anthropogenic carbon dioxide. *Eos.,* 92(24): 201-202.

Global Climate Risk Index. 2020. Bonn: Germanwatch. Available at https://www.germanwatch.org/en/17307 Reterived on 10 October 2022.

Golub, A., T. Hertel, H.L. Lee, S. Rose and B.Sohngen. 2009. The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. *Resour. Energy. Econ*., 31(4): 299-319.

Gougoulias, C., J.M. Clark and L.J. Shaw. 2014. The role of soil microbes in the global carbon cycle: tracking the belowground microbial processing of plant derived carbon for manipulating carbon dynamics in agricultural systems. *J. Sci. Food Agric*., 94(12): 2362-2371.

Gritsch, C., F. Egger, F. Zehetner and S.Z. Boltenstern. 2016. The effect of temperature and moisture on trace gas emissions from deciduous and coniferous leaf litter. *J. Geophys. Res. Biogeosci*, 121(5): 1339-1351.

Hensen, A., U. Skiba and D. Famulari. 2013. Low cost and state of the art methods to measure nitrous oxide emissions. *Environ. Res. Lett.,* 8(2): 025022.

Ijaz, M. and M.A.Goheer. 2020. Emission profile of Pakistan's agriculture: past trends and future projections. *Environ. Dev. Sustain*., 23(2): 1668-1687.

Intergovernmental Panel on Climate Change. 2013. *Key dates in the AR5 schedule.* Available: http://www.ipcc.ch/activities/key_dates_AR5_schedulepdf. Reterived on 10 October 2022.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Climate Change 2007: The Physical Science Basis. Cambridge University Press, UK.

Joseph, S., K. Anitha, V.K. Srivastava, C. Reddy, A.P. Thomas and M.S.R. Murthy. 2012. Rainfall and elevation influence the local-scale distribution of tree community in the southern region of Western Ghats biodiversity hotspot (India). *Int. J. For. Res*., 2012: 1-10.

Keenan, R.J., G.A. Reams, F. Achard, J.V. de Freitas, A. Grainger and E. Lindquis. 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. *Forest Ecol. Manag*., 352: 9-20.

Kesik, M., P. Ambus, R. Baritz, N. Brüggemann, K. Butterbach-Bahl, M. Damm and S. Zechmeister-Boltenstern. 2005. Inventories of N_2O and NO emissions from European forest soils. *Biogeosciences,* 2(4): 353-375.

Körner, C. 2007. The use of altitudein ecological research. *Trends Ecol. Evol*., 22(11): 569-574.

Kweku, D.W., O.Bismark, A. Maxwell, K.A. Desmond, K.B. Danso, E.A. Oti-Mensah and B.B. Adormaa. 2017. Greenhouse effect: greenhouse gases and their impact on global warming. *J. Sci. Res. Rep*., 17(6): 1-9.

Latake, P.T., P. Pawar and A.C.Ranveer. 2015. The greenhouse effect and its impacts on environment. *Int. J. Innov. Res. Cre. Techn*., 1(3): 333-337.

Liu, W., C. Qiao, S. Yang, W. Bai and L. Liu. 2018. Microbial carbon use efficiency and priming effect regulate soil carbon storage under nitrogen deposition by slowing soil organic matter decomposition. *Geoderma.*, 332(2018): 37-44.

Mosier, A.R. 1994. Nitrous oxide emissions from agricultural soils. *Fert. Res.,* 37(3): 191-200.

Olivier, J.G., K.M. Schure and J.A. Peters. 2017. *Trends in global CO_2 and total greenhouse gas emissions.* PBL Netherlands Environmental Assessment Agency, Netherlands.

Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz and D. Hayes. 2011. A large and persistent carbon sink in the world's forests. *Science*, 333(6045): 988-993.

Pörtner, H.O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska and N.M. Weyer. 2019. *The Ocean and Cryosphere in a Changing Climate*. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. 2019 Available from: https://www.ipcc.ch/site/ assets/uploads/sites/3/2019/12/02_SROCC_FM_FINAL.pdf Reterived on 10 October 2022.

Rey, A., E. Pegoraro, V. Tedeschi, I. De Parri, P. G. Jarvis and R. Valentini. 2002. Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. *Glob. Change Biol.,* 8(9): 851-866.

Roberts, T.J. 1997. *The Mammals of Pakistan*. Oxford University Press, Karachi, Pakistan.

Rochette, P. 2011. Towards a standard non-steady-state chamber methodology for measuring soil N_2O emissions. *Anim. Feed Sci. Technol.*, 166(2011): 141-146.

Rochette, P. and S.M. McGinn. 2005. *Methods for measuring soil-surface gas fluxes.*

Rochette. P. and N.S. Eriksen-Hamel. 2008. Chamber measurements of soil nitrous oxide flux- are absolute values reliable. *Soil. Sci. Soc. Amer. J.,* 72(2): 331-342.

Saiz, G., K.A. Byrne, K.L., A.U.S. Butterbach-bahl, R. Kiese, V. Blujdea and E.P. Farrell. 2006. Stand age related effects on soil respiration in a first rotation Sitka spruce chronosequence in central Ireland. *Glob. Change Biol.*, 12(6): 1007-1020.

Schulte-Bisping, H., R. Brumme and E. Priesack. 2003. Nitrous oxide emission inventory of German forest soils. *J. Geophys. Res. Atmos.,* 108(D4): 4132-4140.

Serrano-Silva, N., C. Valenzuela-Encinas, R. Marsch, L.Dendooven and R.J. Alcántara-Hernández. 2014. Changes in methane oxidation activity and methanotrophic community composition in saline alkaline soils. *Extremophiles*, 18(3): 561-571.

Sharma, S., D. Pandey and M. Agrawal. 2016. Global warming potential and sustainable management of three land uses in Varanasi. *Manag. Environ. Qual.,* 27(4): 364-373.

Smith, M.E., J.M. Facelli and T.R. Cavagnaro. 2018. Interactions between soil properties, soil microbes and plants in remnant-grassland and old-field areas: a reciprocal transplant approach. *Plant Soil,* 433(1): 127-145.

Swinehart, D.F. 1962. The beer-lambert law. *J. Chem. Educ.*, 39(7): 333.

USGS Earth Explorer. 2021. Online search, browse display, metadata export, and data download platform for earth science data from the archives of the U.S. Geological Survey. Available from: https://earthexplorer.usgs.gov/-last accessed 25/01/2021

USGS. 2014. *Cement statistics, in: Historical Statistics for Mineral and Material Commodities in the United States, U.S. Geological Survey Data Series 140*, edited by: Kelly, T.D. and G.R. Matos, U.S. Geological Survey, available at: https: //minerals.usgs.gov/minerals/p.

Van Amstel, A. 2012. Methane. A review. *J. Integ. Env. Sci.*, 9(sup1): 5-30.

Vanitchung, S., R. Conrad, N.W. Harvey and A. Chidthaisong. 2011. Fluxes and production pathways of nitrous oxide in different types of tropical forest soils in Thailand. *Soil Sci. Plant Nutr.,* 57(5): 650-658.

Virtanen, R., M. Luoto, T. Rämä, K. Mikkola, J. Hjort, J.A. Grytnes and H.J.B. Birks. 2010. Recent vegetation changes at the high latitude tree line ecotone are controlled by geomorphological disturbance, productivity and diversity. *Glob. Ecol. Biogeogr.,* 19(6): 810-821.

Warlo, H., K. Machacova, N. Nordstrom, M. Maier, T. Laemmel, A. Roos and H. Schack-Kirchner. 2018. Comparison of portable devices for sub-ambient concentration measurements of methane (CH_4) and nitrous oxide (N_2O) in soil research. *Int. J. Environ. Anal. Chem.*, 98(11): 1030-1037.

Xu, M. and Y. Qi. 2001. Spatial and seasonal variations of Q 10 determined by soil respiration measurements at a Sierra Nevadan forest. *Glob. Biogeochem.*, 15(3): 687-696.

Zhang, Y., X. Xu, Z. Li, M. Liu, C. Xu, R. Zhang and W. Luo. 2019. Effects of vegetation restoration on soil quality in degraded karst landscapes of southwest China. *Sci. Total Environ.,* 650(2019): 2657-2665.

Zhao, Z., M.I. Ashraf and F.R. Meng. 2013. Model prediction of soil drainage classes over a large area using a limited number of field samples: A case study in the province of Nova Scotia, Canada. *Can. J. Soil Sci.*, 93(1): 73-83.

Zhu, Q., J. Liu, C. Peng, H. Chen, X. Fang, H. Jiang and X. Zhou. 2014. Modelling methane emissions from natural wetlands by development and application of the TRIPLEX-GHG model. *Geosci. Model Dev.*, 7(3): 981-999.

Zhuang, Q., Y. Lu and M. Chen. 2012. An inventory of global N2O emissions from the soils of natural terrestrial ecosystems. *Atmos. Environ.*, 47(2012): 66-75.

(Received for publication 14 May 2022)