Measurement of Carbon Fluxes in the Tropical Dry Deciduous Forests of Chhattisgarh and Madhya Pradesh under Ecosystem Services Improvement Project

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

Indian Council of Forestry Research and Education
(An Autonomous Body of Ministry of Environment, Forest and Climate Change, Government of India)
P.O. New Forest, Dehradun - 248006 (INDIA)

Measurement of Carbon Fluxes in the Tropical Dry Deciduous Forests of Chhattisgarh and Madhya Pradesh under Ecosystem Services Improvement Project

2023

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

Indian Council of Forestry Research and Education
(An Autonomous Body of Ministry of Environment, Forest and Climate Change, Government of India)
P.O. New Forest, Dehradun - 248006 (INDIA)

Direction and Guidance:
Ms. Kanchan Devi, Director (International Cooperation) and Project Director, ESIP, ICFRE

Report Preparation Team

Edited and Finalized by:

Dr. R.S. Rawat, Project Manager, ESIP, ICFRE,

Dr. Shilpa Gautam Project Coordinator, ESIP, ICFRE

Dr. Rajesh Sharma, ADG (BCC), ICFRE

Prepared by:
Dr. Nepolion Borah, Carbon Monitoring Consultant, ESIP, ICFRE
Dr. Md. Shahid Carbon Sequestration Consultant, ESIP, ICFRE

Published by: Biodiversity and Climate Change Division, Indian Council of Forestry Research and Education P.O. New Forest, Dehradun - 248 006 (INDIA)

ISBN : 978-81-94-9306-8-6

Citation: ICFRE (2023). Measurement of Carbon Fluxes in the Tropical Dry Deciduous Forests of Chhattisgarh and Madhya Pradesh under Ecosystem Services Improvement Project. Indian Council of Forestry Research and Education, Dehradun (INDIA).

सत्यमेव जयते

अरूण सिंह रावत, भा.व.से.
Arun Singh Rawat, IFS

कुलाधिपति, व.अ.सं. विश्वविद्यालय
Chancellor, FRI University

महानिदेशक
भारतीय वानिकी अनुसंधान एवं शिक्षा परिषद्
डाकघर न्यू फॉरेस्ट, देहरादून-248006
(आई एस ओ 9001: 2008 प्रमाणित संस्था)

Director General
Indian Council of Forestry Research and Education
P.O. New Forest, Dehra Dun - 248006
(An ISO 9001 : 2008 Certified Organization)

Foreword

Forests are both source and sink of carbon dioxide due to which forests are an integral part of international agreements dealing with climate change. Forests are considered to provide a climate change mitigation opportunity at comparatively low costs along with other important benefits in the form of ecosystem goods and services. Green India Mission (GIM) is one of the flagship missions for climate change adaptation and mitigation in the forest sector under the National Action Plan for Climate Change. The World Bank funded Ecosystem Services Improvement Project (ESIP) has supported the goals of GIM by demonstrating models for adaptation-based mitigation through sustainable land and ecosystem management.

New tools, techniques and practices for better management and monitoring of forests, including biodiversity and carbon stocks are introduced under ESIP which are considered necessity in the forest sector. ICFRE is one of the project implementing agency and has implemented sub-component on 'Forest Carbon Stocks Measurement, Monitoring and Capacity Building' in selected landscapes of Madhya Pradesh and Chhattisgarh. Two Eddy covariance-based carbon flux towers have bben established under the World Bank funded Ecosystem Services Improvement Project at Khatpura Forest Beat in Budhni Forest Range (Sehore Forest Division, Madhya Pradesh) and Sonhat Forest Beat in Raghunathnagar Forest Range (Balrampur Forest Division, Chhattisgarh) for measurement and monitoing of exchanges of carbon, energy and water fluxes between the atmosphere and vegetation.

I have great pleasure in presenting this report on 'Measurement of Carbon Fluxes in the Tropical Dry Deciduous Forests of Chhattisgarh and Madhya Pradesh under Ecosystem Services Improvement Project'. I am hopeful that the findings of this report will serve as a benchmark for formulating suitable strategies for sustainable management of the forests for enhancing the carbon sequestration potential of the forest ecosystem in the changing climate scenario.

I compliment the entire team of ESIP of ICFRE for bringing out of this report Measurement of Carbon Fluxes in the Tropical Dry Deciduous Forests of Madhya Pradesh and Chhattisgarh.

Dated: 28/07/2022

(Arun Singh Rawat)

पर्यावरण, वन एवं जलवायु परिवर्तन मंत्रालय, भारत सरकार की एक स्वायत परिषद्
An Autonomous Body of Ministry of Environment, Forest & Climate Change, Government of India
दूरभाष/ Phone : 135-2759382 (O)
ई-मेल/ e-mail : dg@icfre.org
EPABX : 0135-2224855, 2224333 (O)
फैक्स/ Fax : 0091-135-2755353

Acknowledgement

I am grateful to the Ministry of Environment, Forest and Climate Change, Government of India and the World Bank for providing necessary guidance and support for measurement and monitoring of the carbon fluxes through eddy covariance based carbon flux towers in the selected forest types of Madhya Pradesh and Chhattisgarh under Ecosystem Services Improvement Project (ESIP).

I am thankful to Sh. Arun Singh Rawat, Director General, ICFRE for constant guidance, support and encouragement for establishment and commission of the carbon flux towers in the states of Chhattisgrah and Madhya Pradesh under ESIP. I am also thankful to Ms. Kanchan Devi, Director (International Cooperation) and Project Director, ESIP, ICFRE for providing continuous supports and guidance for collection of data and preparation of the report.

My sincere thanks to Dr. Anupam Joshi, Senior Environmental Specialist and Team Task Leader, ESIP from World Bank for providing valuable suggestions, guidance and comments on the draft report.

The guidance and supports provided by the officers and consultants of the Green India Mission Directorate, National Afforestation and Eco-development Board, Ministry of Environment, Forest and Climate Change are also gratefully acknowledged.

I am thankful to Sh. S.P. Sharma, Additional Principal Chief Conservator of Forests (GIM) and Nodal Officer, ESIP, Madhya Pradesh and Sh. Arun Pandey, Additional Principal Chief Conservator of Forests and Nodal Officer, ESIP, Chhattisgarh for cooperation and various kinds of support provided for commission of the carbon flux towers in the project areas of Madhya Pradesh and Chhattisgarh for monitoring of the carbon fluxes.

Various kinds of logistic supports provided by the officers and field staff of Budhni Forest Range (Sehore Forest Divisions, State Forest Department of Madhya Pradesh) and Ragunathnagar Forest Range (Balrampur Forest Divisions of Forest and Climate Change Department, Chhattisgarh) from time to time for safety and security of the carbon flux towers are also gratefully acknowledged.

I also express my sincere thanks all the consultants of ESIP for providing supports in execution of field studies, collection of data and maitanance of the carbon flux towers.

Dr. R. S. Rawat, Project Manager, ESIP
on behalf of Report Preparation Team

Contents

Abbreviation Used

AGC	Above Ground Carbon
C	Carbon
CH_4	Methane
CO_2	Carbon Dioxide
EBC	Energy Balance Closure
EC	Eddy Covariance
ESIP	Ecosystem Service Improvement Project
GBPNIHE	Govind Ballabh Pant National Institute of Himalayan Environment
GHG	Greenhouse Gases
GIM	Green India Mission
GPP	Gross Primary Productivity
H	Sensible Heat
H_2O	Water
ICAR	Indian Council of Agricultural Research
ICFRE	Indian Council of Forestry Research and Education
IIRS	Indian Institute of Remote Sensing
IIT	Indian Institute of Technology
IITM	Indian Institute of Tropical Meteorology
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LE	Latent Heat Flux
LULUCF	Land Use, Land-Use Change and Forestry
NEE	Net Ecosystem Exchange
NRSC	National Remote Sensing Centre
PAR	Photosynthetic Active Radiation
PPFD	Photosynthetic Photon Flux Density
R_{eco}	Ecosystem Respiration
RH	Relative Humidity
Rn	Net Radiation
T_{air}	Air Temperature
VPD	Vapor Pressure Deficit

Executive Summary

One of the most significant environmental issues that human civilizations are currently dealing with around the world is excessive emissions of greenhouse gases. One of the primary greenhouse gas causing global warming is carbon dioxide. Forests serve an important part in regulating a region's climate by exchanging energy, water, CO_2, and other chemical components with the atmosphere. It serves as both a carbon sink as well as a carbon source.

The World Bank funded Ecosystem Services Improvement Project aimed to support sequestration of additional carbon of about 10% in the forest areas of Chhattisgarh and Madhya Pradesh over the baseline. Indian Council of Forestry Research and Education installed two carbon flux towers to monitor CO_2 flux and net ecosystem exchange at real time. Key findings of the study on measurement of carbon fluxes in the Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) includes:

- Carbon stock density in Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) was reported to be 74.23 t ha^{-1} and 65.75 t ha^{-1}, respectively. The top five aboveground carbon stock contributing tree species in Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) were *Terminalia tomentosa, Madhuca latifolia, Buchanania cochinchinensis, Chloroxylon swietenia* and *Anogeissus latifolia*. Similarly, top five aboveground carbon stock contributing tree species in Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) were *Shorea robusta, Terminalia bellirica, Madhuca latifolia, Boswellia serrata* and *Terminalia tomentosa*.
- Photosynthetically Active Radiation, one of the crucial parameters in carbon cycle in terrestrial ecosystem and surface energy cycle, ranged from 392.71 to 890.90 $\mu mol m^{-2} s^{-1}$ at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 156.65 to 910.91 $\mu mol m^{-2} s^{-1}$ at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).
- The energy balance closure is used to assess the reliability and accuracy of surface flux measurement. The average monthly energy balance ranged from 145.05 to 305.98 Wm^{-2} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 132.39 to 264.45 Wm^{-2} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).
- The recorded annual mean net ecosystem exchange at both the sites indicate the net sink of carbon to the atmosphere over study period. The CO_2 uptake from the atmosphere has been reported from the month of July to February continuously at both the forests. Forests are acting as source of carbon from March to June.
- The mean net ecosystem exchange was recorded lower in the wet seasons than dry season at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).
- The highest sequestration of CO_2 was recorded in the month of August at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and September at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).
- The cumulative net ecosystem exchange recorded for Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) was 5.47 and 4.96 t C ha^{-1}, respectively in 1st year and 2nd year and for Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) was 4.15 and 4.66 t C ha^{-1}.
- The carbon uptake reached peak during before noon hours (1000–1100 hrs) in both wet season dry season, and then started to diminish at both forests. In the evening, net ecosystem exchange changed from a negative value to a positive value indicating carbon emission to the atmosphere.
- Environmental parameters such as air temperature, photosynthetically active radiation, vapour pressure deficit and soil temperature were significantly correlated with net ecosystem exchange at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).
- Some Government organization such as NRSC, IIRS, IITM, ICFRE, etc. has established carbon flux towers in different parts of the country.

There is a need to develop a mechanism for networking of the already installed eddy covariance-based carbon flux towers in the form of Indo Flux for comprehensive observation, sharing of the data and results for further preparation of the country level report on the carbon fluxes of the forests. Subsequently networking of carbon flux towers can also be done with Asia Flux.

- Long term measurements of carbon fluxes provide intense and detailed understanding of the carbon cycle processes. Continuation of ongoing measurements could help in predicting net carbon uptake at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) in near future and also helpful in developing suitable mitigation and adaptation strategies for changing climate.

01

Introduction

The environmental problems have become more and more prominent with the rapid industrial development and land use change (IPCC, 2014). Intergovernmental Panel on Climate Change has reported that climate is changing faster than expected. Excessive emissions of carbon dioxide and other greenhouse gases are currently one of the most serious environmental problems that societies are facing in different parts of the globe and need to be resolved (IPCC, 2021). Carbon dioxide is the most dominant greenhouse gas but apart from this there are number of other gases such as methane, nitrous oxide and other trace gases that are causing global climate change (Ritchie *et al*., 2020).

Forests play a crucial role in regulating climate of a region through exchange of energy, water, CO_2 and other chemical components with the atmosphere (Bonan, 2008). Forest ecosystem is the largest carbon reservoir among the terrestrial ecosystems. It is estimated that about 662 Gt (@163 t/ha) of carbon are stored in the forest ecosystems across the globe (FAO, 2020). These forests could be the most cost-effective climate change mitigation option if adequate measures are taken to reduce deforestation and forest degradation (IPCC, 2014).

Forests act as both sink and source of carbon and play a crucial role in mitigating climate change by absorbing atmospheric carbon dioxide through photosynthesis (Bonan, 2008; Chen *et al*., 2009). It is estimated that forests can absorb about 25% of the atmospheric CO_2 emitted by the anthropogenic activities (King *et al*., 2007; Domke *et al*., 2018; Keenan and Williams, 2018; Zhou *et al*., 2022). Therefore, carbon sequestration by the forest is considered as one of most potential natural climate change solutions in maintaining carbon balance (Stocker *et al.,* 2013; Fargione *et al*., 2018). On the other hand, deforestation and forest degradation act as source of carbon emission (Jiang *et al.,* 2022). Quantification of forest carbon stocks and regular monitoring of carbon fluxes over forest ecosystem play an important role in implementation of suitable forest management practices and strategies for climate change mitigation (Gray and Whittier, 2014; Yu *et al*., 2021).

Gross primary productivity (GPP), net primary productivity (NPP) and net ecosystem exchange (NEE) are the major components in measuring and monitoring of carbon flow at ecosystem level (Boisvenue and Running, 2006). GPP is the total uptake of carbon through photosynthesis by plants in the ecosystem while NPP is the total carbon uptake by the autotrophs excluding the carbon losses due to respiration. NEE is a measure of the net exchange of carbon between an ecosystem and the atmosphere. The net photosynthetic uptake and release of carbon dioxide by respiration from autotrophs and heterotrophs, represents the net exchange of carbon dioxide between terrestrial ecosystems and the atmosphere (Xiao *et al*., 2011).

Accurate estimation of NEE at local, regional and global level improves the understanding of carbon flux in atmosphere and biosphere and the context of global change and facilitate climate policy-making (Xiao and Moody, 2005; Waring and Running 2007). Accurate quantification of carbon stocks across different ecosystems increases the understanding of the magnitude of carbon density and carbon fluxes. Precise and accurate estimations are the key processes in formulating the climate change mitigation strategies (IPCC, 2007).

Eddy covariance-based techniques for CO_2 flux measurement: Measuring temporal change, in biomass and underlying soil carbon pool were the conventional technique for estimating the carbon fluxes in a forest ecosystem over several years (Amundson *et al.,* 1998 and Clark *et al.,* 2001). The conventional field inventories using allometric equations are practically difficult to measure an accurate and consistent carbon fluxes at daily, monthly, and yearly time scales. Eddy covariance (EC) based technique has been developed as an alternative method to accurately quantify the net ecosystem exchange which directly measures the CO_2 fluxes between canopy and atmosphere (Running *et al.,* 1999; Canadell *et al*., 2000). Presently, eddy covariance-based technique is considered one of the best methods for accurately quantifying carbon flux (Zhou *et al.*, 2022). This technique is best suited for ecosystem level monitoring as its features are underlying micrometeorological principles, continuous monitoring, little perturbation or damaging of the system sampled and footprint (Campioli *et al.*, 2016).

The EC based technique measures the CO_2, CH_4, water vapour (H_2O), sensible heat (H), latent heat (LE), and soil heat fluxes. Therefore, this technique can be used to study carbon balance, gross primary productivity (GPP), ecosystem respiration (R_{eco}), net ecosystem exchange (NEE), hydrological and energy partitioning, water loss and energy balance in a particular ecosystem. It has been widely used for validation and fine-tuning of global climate and weather models, ecological models, biogeochemical models, and downscaling of the remote sensing data from satellites and aircraft (Chatterjee *et al*., 2021). Apart from the monitoring of GHGs in forests and agriculture, it has wide use in many industrial monitoring, landfill and environmental management, and monitoring of lakes and other water bodies.

Eddy covariance-based carbon flux technique provides a direct measure of net carbon dioxide exchange across the canopy and atmosphere boundary. Theory of micrometeorological is used to interpret the measurements resulting from covariance between vertical wind velocity and scalar concentration fluctuations (Baldoochi *et al*., 1988). This method helps to correlate by quantifying the carbon dioxide exchange rates of the ecosystem covered by the sensor responds to the environmental disturbances. Therefore, this method helps in answering the management-based queries practiced in that region and further in achieving the sustainable management of the forest. Measurement of the gas fluxes using this technique is possible by modern instruments and software which relies on direct and very fast measurements of actual gas transport by a 3-dimensional wind speed in real time *in-situ*, resulting in calculations of turbulent fluxes within the atmospheric boundary layer (Burba and Anderson, 2010).

The CO_2 flux describes how much of CO_2 moves through a unit area per unit time. It depends upon three things (1) number of things crossing an area, (2) size of an area being crossed, and (3) the time it takes to cross this area. In atmospheric conditions, the CO_2 flow can be imagined as a horizontal flow of numerous rotating eddies which has three dimensional components. The general principle of eddy covariance measurements is covariance between the concentration of interest and vertical wind speed in the eddies (Burba and Anderson, 2010). To quantify these measurements, sophisticated instruments are required to quantify the high-speed fluctuations in concentration, density or temperature with greater accuracy. It can be better explained by the formula given below that expresses the mean flux density of CO_2 averaged over some time span (such as an hour):

$$F = \overline{\rho_a}.\ \overline{w'c'}$$

Where, ρ_a= air density
c= CO_2 mixing ratio
w= vertical wind velocity

The major advantages of EC techniques include: (a) provides a continuous *in-situ* measurements over the large area without disturbing the area over which fluxes are measured, (b) the flux data are highly reliable, defensible and verifiable, (c) the data obtained are measured with fast sampling and high precision, (d) the measurement system is automated and provides continuous data.

However, there are some limitation in this technique such as (a) there are chances of having random measurement errors. The source of such errors is due to power fluctuations, insects and dirt contamination in the sensors and errors associated with turbulent transport, (b) the technique is mathematically complex and requires significant care in setting up and processing of data (c) Eddy towers can provide information specific to a single ecosystem type or condition. If mixed ecosystem is present then it is very difficult to predict which component of the system contributes to the flux, (d) sometime noisy flux is obtained and this uncertainty is mainly because of random measurement error, (e) it requires a number of assumption and correction and demands careful design, execution and processing, (f) the study area needed to be flat, homogeneous and must represent the similar ecology for measurement, which is sometimes not possible in natural forest ecosystem.

Ecosystem Services Improvement Project (ESIP)

The World Bank funded Ecosystem Services Improvement Project (ESIP) implemented since 2018 in the States of Chhattisgarh and Madhya Pradesh and supported the goals of the Green India Mission (GIM) by demonstrating models for adaptation-based mitigation measures through sustainable land and ecosystem management (SLEM) and also to provide livelihood benefits to the local communities. ESIP, in many ways, tried to bring a new and novel approach to address some of the challenges in management of land and ecosystems. Different SLEM activities under ESIP demonstrate the potential for nation-wide scaling up of GIM. It also introduced new tools and technologies for better management of the natural resources, including biodiversity and carbon stocks.

Implementation of the ESIP activities aims to support sequestration of additional carbon of about 10% in the forest areas of Chhattisgarh and Madhya Pradesh over the baseline. It also presents a good opportunity to improve the carbon sequestration potential of the entire target area of GIM through scaling up of successful demonstrative pilots. Indian Council of Forestry Research and Education (ICFRE) developed the baseline reports of the forest carbon stocks of the project areas of Madhya Pradesh and Chhattisgarh (ICFRE, 2020 a and 2020 b).

ICFRE implemented the sub-component on 'Forest carbon stocks measuring, monitoring and capacity building' besides the component on 'Scaling up of sustainable land and ecosystem management practices' under ESIP. Carbon flux towers in the representative forest areas in Chhattisgarh and Madhya Pradesh are established under the ESIP to monitor CO_2 flux and NEE at real time. Measuring and analysing the CO_2 fluxes and NEE are very important indicators for knowing the source and sink nature of the forests. Realtime CO_2 flux/ NEE data also helps the decision makers in taking quick action at local or regional level for climate change mitigation programs. Understanding the temporal and seasonal patterns/ behaviour of CO_2 fluxes and NEE plays a crucial role in the climate change modelling and strategies (Ahongshangbam, 2014). Beside these, carbon stocks and GPP estimated by inventory or remote sensing-based modelling can be validated with the CO_2 flux data.

02

Materials and Method

2.1. Site Description

Eddy covariance-based carbon flux towers are established by ICFRE under the World Bank funded Ecosystem Services Improvement Project at Khatpura Forest Beat in Budhni Forest Range (Sehore Forest Division, Madhya Pradesh) and Sonhat Forest Beat in Raghunathnagar Forest Range (Balrampur Forest Division, Chhattisgarh). Khatpura Forest Beat occupies a total land area of 597 ha and Sonhat Forest Beat has total 2198.40 ha land area. Details of the eddy covariance-based carbon flux tower sites are given in Table 1. Khatpura Forest Beat represents the Northern Mixed Deciduous Forest while Sonhat Forest Beat represent the Southern Mixed Deciduous Forest.

Density, basal area and carbon stocks of the Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) were carried out by laying out four 0.1 ha nested plots in the four directions of the carbon flux towers following Resource Manual titled Measurement of Forest Carbon Stocks for Capacity Building of State Forest Department developed under ESIP (ICFRE, 2020 c). The tree density at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) was recorded 465 trees ha^{-1} and in Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) was 535 trees ha^{-1}. The estimated carbon density for Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) were 74.23 t ha^{-1}) and 65.75 t ha^{-1}, respectively (Table 1). Distribution of carbon stocks in different pools of the Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) are shown in the Figure 1. The aboveground carbon stock was estimated to 35.06 t ha^{-1} and 28.36 t ha^{-1}, respectively in Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). The top five aboveground carbon stock contributing tree species in Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) were *Terminalia tomentosa* (19.64 t ha^{-1}), *Madhuca latifolia* (7.99 t ha^{-1}), *Buchanania cochinchinensis* (4.30 t ha^{-1}), *Chloroxylon swietenia* (3.25 t ha^{-1}) and *Anogeissus latifolia* (1.50 t ha^{-1}). Similarly, top five aboveground carbon stock contributing tree species in Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) were *Shorea robusta* (10.52 t ha^{-1}), *Terminalia bellirica* (5.63 t ha^{-1}), *Madhuca latifolia* (5.30 t ha^{-1}), *Boswellia serrata* (3.39 t ha^{-1}) and *Terminalia tomentosa* (2.75 t ha^{-1}) (Table 2).

Distribution of aboveground C-stock of tree species in different girth classes showed that most of the aboveground C-stocks were in 70-80 cm and 50-60 cm girth classes, respectively, at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Figure 2). This indicates that forests near the carbon flux towers are in growing stages and have potential to store more carbon in near future. Density distribution of tree species in different girth classes in Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) reveals normal density distribution curve *i.e.*, density of tree species decreases with increase in girth classes. However, in Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh), the density distribution curve followed zig-zag pattern (Figure 2). Highest tree density was recorded in 50-60 cm girth class. Lower tree density in lower girt classes (30-40 cm and 40-50 cm) indicates that the forest might had faced some disturbances such as forest fire, etc., in past that affect the regeneration of the tree species.

Table-1: Description of the eddy covariance-based carbon flux tower sites

Site name	Khatpura Forest Beat	Sonhat Forest Beat
Location	Budhni Forest Range, Sehore Forest Division (Madhya Pradesh)	Raghunathnagar Forest Range, Ambikapur Forest Division (Chhattisgarh)
Area (ha)	597.0	2198.40
Terrain type	Flat	Flat
Slope	<2 degree	<2 degree
Fetch	500-700 m	500-700 m
Vegetation type	Northern Mixed Deciduous Forest	Southern Mixed Deciduous Forest

Tree density (trees ha^{-1})	465 ± 41	535 ± 34
Tree Basal area (m^2 ha^{-1})	16.05 ± 1.50	12.48 ± 0.86
Total carbon stocks (t)	44315.31	144544.8
Carbon stock density (t ha^{-1})	74.23 ± 8.96	65.75 ± 3.89
Canopy height	12-15 m	25-28 m
Measurement height	22 m	32 m
Sampling frequency	10 Hz	10 Hz
Averaging time	30 minutes	30 minutes
Data Logger	Campbell (CR 3000)	Campbell (CR 3000)
Data Storage	32 GB Data Card	32 GB Data Card

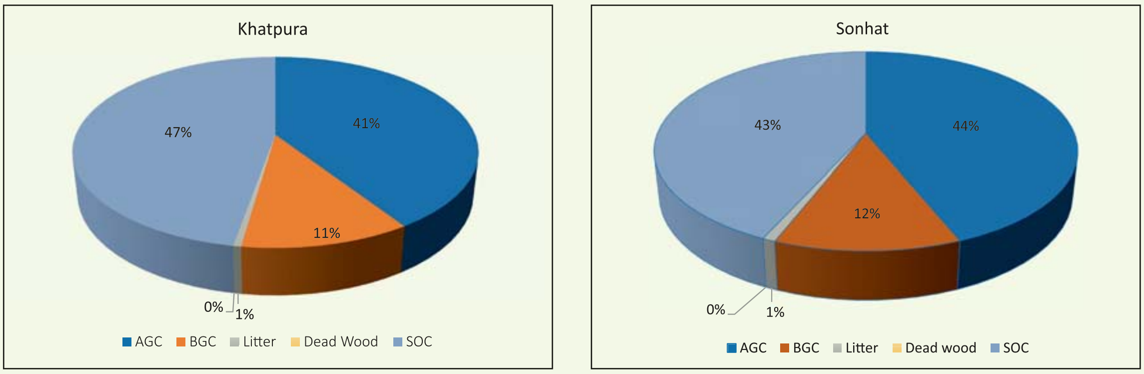


Fig. 1.: Distribution of carbon stocks in the five pools at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

Table-2: Density, basal area, aboveground carbon stock (AGC), below ground carbon stock (BGC) and total carbon stocks of tree species of Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

S. No.	Species	Density (tree ha^{-1})	Basal area (m^{2}ha^{-1})	AGC Stock (t C ha^{-1})	BGC Stock (t C ha^{-1})	Total Carbon Stock (t C ha^{-1})
Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh)						
1	*Anogeissus latifolia*	5	0.39	1.17	0.33	1.50
2	*Buchanania cochinchinensis*	85	2.88	3.36	0.94	4.30
3	*Chloroxylon swietenia*	95	2.09	2.54	0.71	3.25
4	*Diospyros melanoxylon*	12.5	0.41	0.81	0.23	1.04
5	*Lagerstroemia parviflora*	15	0.24	0.32	0.09	0.41
6	*Madhuca latifolia*	72.5	3.25	6.24	1.75	7.99
7	*Pterocarpus marsupium*	2.5	0.13	0.33	0.09	0.42
8	*Terminalia tomentosa*	177.5	6.66	15.34	4.3	19.64
Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)						
1	*Accacia catechu*	10	0.15	0.12	0.04	0.15
2	*Anogeissus latifolia*	32.5	0.48	2.02	0.57	2.59
3	*Boswellia serrata*	15	0.56	2.65	0.74	3.39
4	*Buchanania cochinchinensis*	20	0.22	0.19	0.05	0.24
5	*Cleistanthus collinus*	5	0.04	0.05	0.01	0.06
6	*Diospyros melanoxylon*	25	1.03	2.24	0.63	2.87
7	*Lannea coromandelica*	15	0.25	0.29	0.08	0.37
8	*Madhuca latifolia*	87.5	2.08	4.14	1.16	5.30
9	*Phyllanthus emblica*	2.5	0.02	0.03	0.01	0.04
10	*Pterocarpus marsupium*	2.5	0.04	0.09	0.03	0.12

11	*Saccopetalum toemtosum*	12.5	0.19	0.33	0.09	0.42
12	*Semecarpus anacardium*	10	0.15	0.26	0.07	0.34
13	*Shorea rubusta*	132.5	3.55	8.22	2.30	10.52
14	*Soymida febrifuga*	2.5	0.07	0.22	0.06	0.28
15	*Terminalia bellirica*	82.5	2.08	4.40	1.23	5.63
16	*Terminalia chebula*	15	0.34	0.71	0.20	0.91
17	*Terminalia tomentosa*	50	1.04	2.15	0.60	2.75
18	*Zizyphus xylopyra*	15	0.19	0.44	0.12	0.56

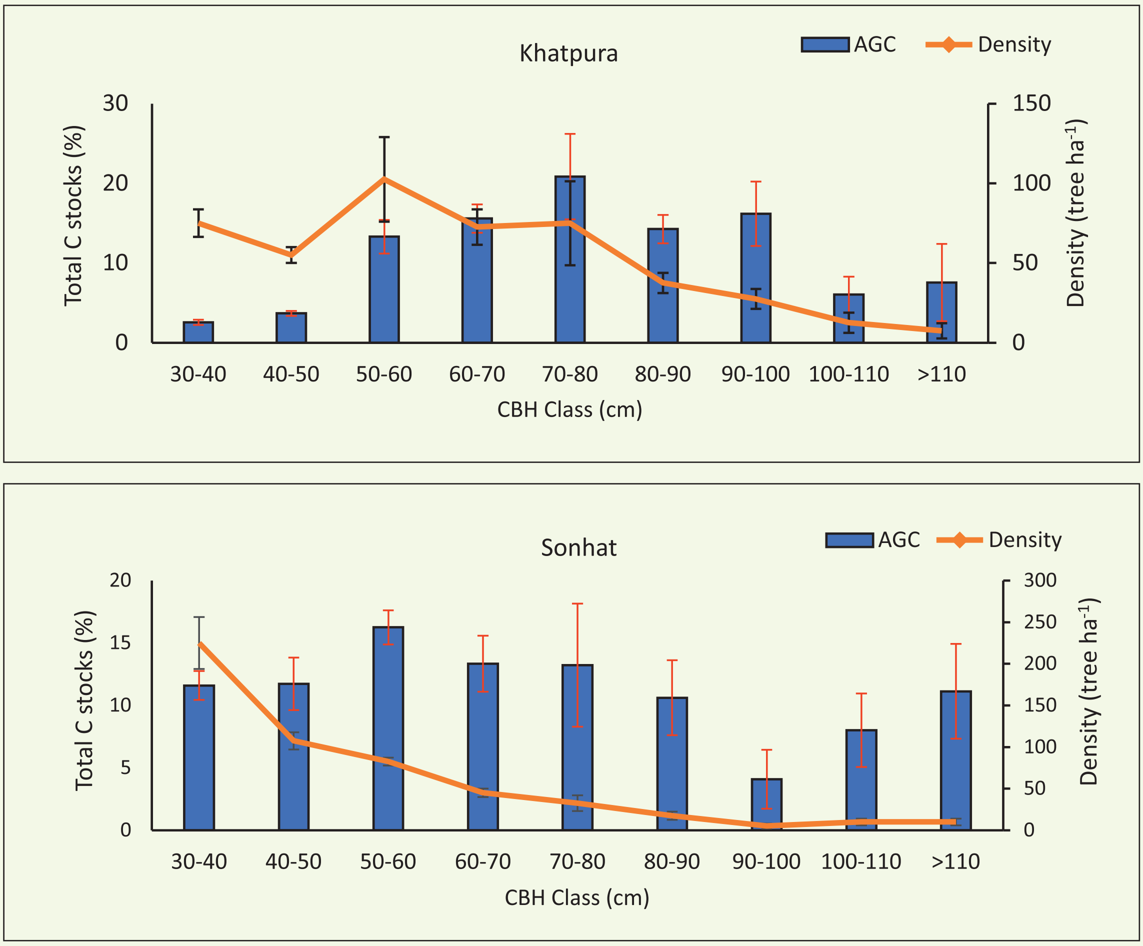


Fig. 2.: Distribution of tree density and aboveground carbon stocks (AGC, %) in different girth classes in Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).

2.2. Instrumentation

Following instrument/sensors are being used to collect carbon flux data and other micrometeorological data from the carbon flux towers installed at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh):

1. IRGASON: Mid-Infrared absorption gas analyser integrated with a three-dimensional sonic anemometer (IRGASON) is a sensor which is responsible for measurements of absolute densities of carbon dioxide and water vapor, while the sonic anemometer measures orthogonal wind components (Figure 3). It synchronizes gas and wind data, essential for valid flux calculations using the eddy-covariance method and based on Reynolds decomposition formula. To compute carbon dioxide fluxes using the eddy covariance method, the IRGASON measures absolute carbon dioxide, water vapor densities, three-dimensional wind speed, sonic air temperature, air temperature and barometric pressure. The standard outputs from this sensor are:

- u_x, u_y, and u_z orthogonal wind components
- sonic temperature (based on the measurement of c, the speed of sound)
- sonic diagnostic flags
- CO_2 density, H_2O density
- gas analyzer diagnostic flags
- air temperature, air pressure
- CO_2 signal strength, H_2O signal strength
- air temperature and air pressure are auxiliary sensor inputs

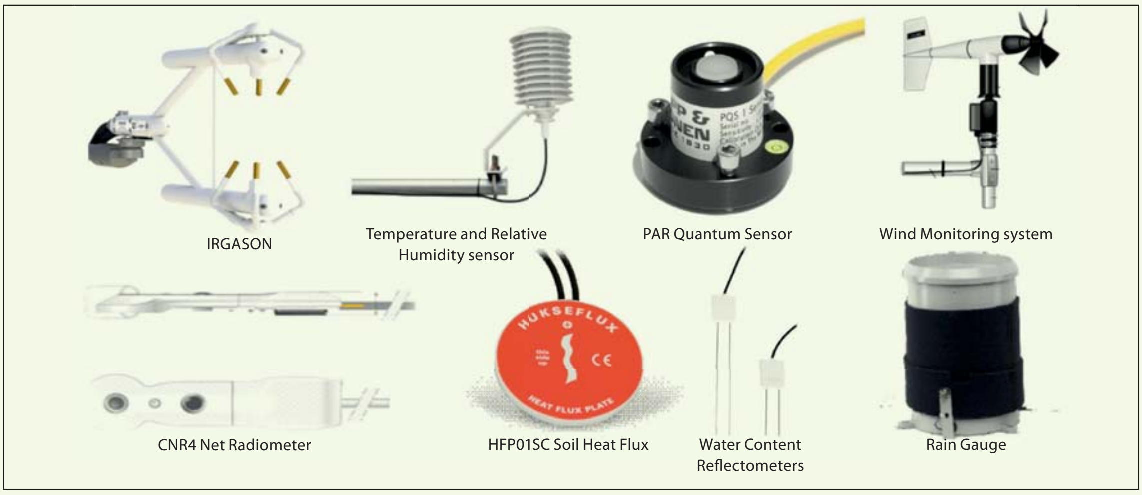
These outputs are recorded at 10 Hz frequency which means the turbulence helps in measuring and providing these outputs 10 times in one second which is further processed to get the values at half hourly to monthly to yearly for effective decision making based on the output at high temporal scale. It is mounted at 22 m and 32 m height on the carbon flux towers, respectively at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). The IRGASON is a field rugged instrument and it is tolerant to window contamination, and the IRGASON optics feature angled windows is better to shed water. Easy access to chemical bottles makes it serviceable in the field. Very low power consumption (5 W at 25°C) minimizes flux errors due to body heating and makes solar powered applications more economical and convenient. This instrument/ sensor makes fast measurements due to the turbulent fluctuations that occur very rapidly in the form of up and down movements and consequently the number of molecules.

2. Temperature and Relative Humidity Sensor: This sensor is for accurate measurement of temperature and relative humidity and is mounted at six places on the tower at the height of 2, 6, 10, 16, 32, 40 m and the data reflect the vertical profile (distribution) measurement. HC2AS3 is the model of the sensor utilized for the study of air temperature and relative humidity. The advantage of this model is its outstanding accuracy, repeatability and long-term stability because the probe includes a filter which protects the sensor from dust and particles to maintain superior performance and reliability. The range of application is -40°C to 100°C and 0-100 % RH at an accuracy of ±0.8% and ± 0.1 Kelvin (k) at 23°C.

3. Wind Speed and Direction Sensor: This sensor measures horizontal wind speed and direction. This sensor is mounted at six places on the tower at the height of 2, 6, 10, 16, 32, 40 m and the data reflect the vertical profile of wind (distribution) measurement. The range varies from 0 to 100 m/s and accuracy for wind speed varies from ±0.3 m/s (±0.6 mph).

4. PAR Quantum Sensor: Light which a plant can use for photosynthesis process is called Photosynthetically Active Radiation (PAR). Light plays a crucial part in plant growth. The model number of the sensor used is PQS 1 and this instrument is accurate and provides continuous measurement of PAR. The amount of PAR is a key research parameter which helps in measuring the energy balance in a forest ecosystem. It can be measured above, within and below the forest canopy to retrieve valuable data on plant physiology and leaf area. The measurement ranges from 0 to 4000 umol $m^2 s^{-1}$. It is mounted at the height of 2 m and 18 m.

5. Net Radiometer: The CNR4 is a four-component net radiometer that measures the energy balance between incoming short-wave and long-wave far infrared radiation versus surface-reflected short-wave and outgoing long-wave radiation. It consists of two pyranometer for measuring solar radiation and two pyrgeometers for measuring far infrared radiation. It is meant for outdoor


IRGASON

Temperature and Relative Humidity sensor

PAR Quantum Sensor

Wind Monitoring system

CNR4 Net Radiometer

HFP01SC Soil Heat Flux

Water Content Reflectometers

Rain Gauge

Fig. 3.: Instrument/ sensors installed in the carbon flux towers

purpose therefore, it is weatherproof and of low maintenance. It is mounted at 18 m on the flux tower. The Net Radiometer, with model number CNR 4, is intended for the analysis of the radiation balance of solar and far infrared radiation. The most common application is the measurement of net (total) radiation at the earth's surface. The spectral range of the pyranometer is 300-2800 nm whereas of the pyrgeometer is 4.5 to 42 µm.

6. Soil Heat Flux Plate: This instrument consists of a thermopile and a film heater. The thermopile measures temperature gradients across the plate. The film heater is used to generate a heat flux through the plate. The amount of power used to generate the calibration heat flux is measured by the data logger. It has two cables the first one is the signal output cable and the second is the heater input cable. It is known for high degree of measurement accuracy with expected accuracy of ±3% of reading.

7. Water Content Reflectometers: The CS650 and CS655 are model numbers for the measuring multiparameter and uses innovative techniques to monitor soil volumetric water content, bulk electrical conductivity, and temperature of soils. The CS650 has 30 cm length rods, whereas the CS655 has 12 cm length rods. The sensor rods can insert vertically into the soil surface or buried at any orientation to the surface. It estimates soil water content for a wide range of mineral soils.

8. Tipping Bucket Rain Gauge: It is one of the precision instruments and includes a siphoning mechanism that allows the rain to flow at a steady rate regardless of rainfall intensity. The siphon reduces typical rain bucket errors and produces accurate measurements for up to 50 cm per hour. It is ideal for intense rainfall events and helps in water content measurement through rainfall and measures 0.01-inch increments. The measurement range varies from 0 to 700 mm/hr.

9. Field Camera: It produces HD video and photos of up to 5 megapixels and has an internal 16 GB camera memory which enables the camera to archive photos and video internally. This is mounted at 42 m. CCFC (Outdoor Observation and Surveillance Field Camera) camera can operate over a wide temperature range and has several advanced power saving modes to suit a variety of needs. It has been designed to work in harsh environments, this camera operates at temperatures that range from -40°C to 60°C. This camera utilizes high intensity non-visible infrared (850 nm) LEDs for night vision illumination.

2.3. Data Processing and Analysis

Eddy fluxes (CO_2, H_2O and sensible heat) were calculated as 30-minute block averages with the help of EasyFlux PC software (McMillen, 1988**)**. The eddy covariance method relies on the availability of energy and turbulence in the surface layer. Therefore, there may be some uncertainties in the eddy covariance measurement (Loescher *et al.*, 2006). The uncertainties of the eddy covariance measurement could be due to overestimation of available energy and underestimation of turbulent energy (McGloin *et al.*, 2018). Possible reasons for the overestimation of available energy include overestimation of Rn measurement and underestimation of energy storage items such as soil, air and vegetation (Foken, 2008).

The measure taken to reduce the possible uncertainties in EC data includes splitting it into 30 minutes files; despiking (Vickers and Mahrt, 1997); block averaging; 2D coordinate rotation; spectra correction (Moncrieff *et al.*, 1997, 2004); Webb, Pearman and Leuning (WPL) correction (Webb *et al.*, 1980) and conducting quality control (Burba, 2013). The WPL correction was used to estimate CO_2 and H_2O fluxes. The WPL correction is necessary because fluctuations in temperature and humidity cause fluctuations in trace gas concentrations and that can simulate a flux for instance of CO_2 or modify its size. The Cospectral analyses of CO_2, H_2O, and heat flux measurements were done to assess the reliability of the flux data and to verify if appropriate averaging intervals have been used to capture all of the flux-carrying eddies (Kaimal *et al.*, 1972).

The net ecosystem exchange (NEE) of CO_2 between the forest and the atmosphere was computed as:

$$NEE = \overline{wc'} + \frac{\partial}{\partial t}\int_{0}^{h} \overline{c(z)dz}$$

Where, the first term on the right-hand side is the covariance between vertical wind velocity fluctuations (*w*') and fluctuations in the concentration of the scalar (*c*', CO_2). The second term is the rate of change in the canopy storage, where *z* is the height above the ground surface, *h* is the flux measurement height, *t* is time, and the overbar denotes a time average (Baldocchi *et al.*, 1988). The vertical coordinate for wind velocities is positive upward, thus positive values for fluxes denote emission and negative values denote uptake. Concentrations of CO_2 and H_2O were calculated using output from the IRGA's raw signal.

The post-processing included: (a) elimination of data collected during the rainy periods, (b) removal of negative NEE night-time data, (c) removal of positive data during day time (when photosynthetically active radiation (PAR) >100) and (d) outlier removal by discarding the absolute NEE values (NEE > 50 µmol m^{-2} s^{-1} and NEE < -50 µmol m^{-2} s^{-1}) (Fei *et al*., 2018). Data gap filling was carried out using the mean diurnal variation method (Falge *et al*., 2002).

The NEE values were separated into the component fluxes of ecosystem respiration (R_{eco}) and gross primary production (GPP) in order to observe patterns of CO_2 exchange. The NEE measurement during the daytime is the result of both photosynthesis and respiration, but at night EC it represents only respiration (R_{eco}). Therefore, night time NEE was used to estimate the R_{eco} during well-mixed periods where the friction velocity; was greater than or equal to 0.20 m s^{-1} (Hutyra *et al*., 2007).

$$u^* = \sqrt{-1^* \overline{w'u'}}$$

An exponential equation (Eq. 1) was developed using night-time NEE and corresponding air temperature (T_{air}) for each month for partitioning of NEE (Zhang *et al*., 2006; Wang *et al*., 2008; Artigas *et al*., 2015). For calculation of daytime R_{eco}, it is assumed that the temperature response of daytime R_{eco} resembles with that of night-time R_{eco}. The temporal changes in R_{eco} is influenced by seasonal variability of environmental factors, in particular temperature, soil moisture or precipitation, photosynthesis and phenology etc. (Migliavacca *et al*., 2015; Reichstein and Beer, 2008). Therefore, the exponential relationship between T_{air} and NEE was established for each month (Annexure I) in order to account for the change in phenology and to incorporate the effect of soil moisture to some extent.

$$NEE_{nighmt} = a\ exp^{bT_{air}} \qquad \text{Eq.1}$$

where NEE_{night} is night-time ecosystem respiration and T_{air} is night-time mean air temperature. The constants a and b were determined by using non-linear optimization.

The GPP is estimated using following equation (Eq.2)

$$GPP = -NEE + R_{eco} \qquad \text{Eq.2}$$

The sign convention used was such that CO_2 flux from the atmosphere to the surface was negative but the GPP and RE were always positive (Watham *et al*., 2020).

03

Result and Discussion

3.1. Weather and Climate

The monthly average meteorological parameters of the Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) for the period from April 2021 to March 2023 are given in the Table 3 and 4. Highest precipitation was recorded in the month of August 2022 for Northern Mixed Deciduous Forest, Khatpura, Madhya Pradesh (334.05 mm) and Southern Mixed Deciduous Forest, Sonhat, Chhattisgarh (722.72 mm). Very scattered rainfall was recorded at both forests during the dry season (from October to April). The highest mean temperature was recorded in the month of April, 2021 at Northern Mixed Deciduous Forest, Khatpura, Madhya Pradesh (33.23° C) and in the month of May, 2022 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (31.52° C). January 2022 was recorded the coldest month at Northern Mixed Deciduous Forest, Khatpura, Madhya Pradesh and Southern Mixed Deciduous Forest, Sonhat, Chhattisgarh (17.17° C and 15.94° C respectively).

The highest mean daily wind speed recorded by the sonic anemometer at top of the carbon flux tower was 2.22 ms-1 in the month of June 2022 at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and 2.46 ms-1 in the month of July 2022 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). The highest average mixing ratio (u*) were also recorded in month of June 2022 at Northern Mixed Deciduous Forest, Khatpura, Madhya Pradesh (0.58) and in the month of April 2022 at Southern Mixed Deciduous Forest, Sonhat, Chhattisgarh (0.40). The mean relative humidity (RH) ranged from 9.74% to 84.06% at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 14.71% to 79.82% at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) during the study period (Table 5). The mean ambient pressure remains more or less stable in both the sites ranging from 95.5 to 97.9 kPa.

3.2. Net Radiation and PAR

The net radiation (Rn), also called net flux is the difference between all incoming radiation and all outgoing radiation. In places where radiant energy flows in faster than it flows out, net radiation is positive, providing an energy surplus. The net radiation is the total energy that influence the climatic condition of an area. The net radiation (R_n) is the major energy input of the forest ecosystem and drove other processes such as the evaporation of water, photosynthesis, and temperature changes (Jia *et al*., 2023). In this study, net radiation flux (Rn) during day time was recorded highest in the month of March 2022 at Northern Mixed Deciduous Forest, Khatpura, Madhya Pradesh (614.36 Wm^{-2}) and in the month of June, 2022 at Southern Mixed Deciduous Forest, Sonhat, Chhattisgarh (540.14 Wm^{-2}). The lowest Rn was recorded at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) in the month of December, 2022 (190.82 Wm^{-2}) and at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) in the month of January, 2023 (254.77 Wm^{-2}). Rn at night hours ranged from -70.19 to -3.09 Wm^{-2} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from-67.08 to -18.53 Wm^{-2} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Table 4).

Photosynthetically Active Radiation (PAR) is the amount of light energy available for photosynthesis, which is the light in the 400 to 700 nanometer wavelength. PAR is the crucial parameters in carbon cycle in terrestrial ecosystem and surface energy cycle (Niu *et al*., 2018). In the study, PAR at day time ranged from 392.71 to 890.90 µmolm^{-2}s^{-1} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 456.65 to 910.91 µmolm^{-2}s^{-1} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). The highest mean PAR (890.90 µmolm^{-2}s^{-1}) was recorded in the month of August 2022 at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and 910.91 µmolm^{-2} s^{-1} in the month of March 2023 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).

3.3. Energy Flux

Latent heat is the energy absorbed by or released from a substance during a phase change from a gas to a liquid or a solid or vice versa. The latent heat (LE) is the primary factor involved in the formation of convective clouds and the stability/ instability of the atmosphere. The latent heat (LE) observed during the study period ranged from 24.41 to 256.26 Wm^{-2} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 29.31 to 192.36 Wm^{-2} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Table 6).

The energy required to change the temperature of a substance without changing its original state is called sensible heat (H). The temperature change can come from the absorption of sunlight by the soil or the air itself or it can come from contact with the warmer air caused by release of latent heat (by direct conduction). Energy moves using both latent and sensible heat are responsible for the movement of energy through the atmosphere and create wind and vertical motions. In the present study, the monthly mean sensible heat flux at day time ranged from 38.46 to 180.56 Wm^{-2} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 40.24 to 173.49 Wm^{-2} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). The highest mean H was recorded in the month of May, 2022 at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and in the month of April, 2022 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). The monthly lowest mean H was recorded in the month of October, 2022 at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and in the month of August, 2021 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).

The energy balance closure (EBC) represents the sum of atmospheric sensible (H) and latent heat (LE). It is used to assess the reliability and accuracy of surface flux measurement. The highest monthly energy balance (305.98 Wm^{-2}) was recorded in the month of June, 2021 and lowest (145.05 Wm^{-2}) in the month of November 2022 at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh). The energy balance at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) ranged from 132.39 to 254.90 Wm^{-2}. The highest monthly mean energy balance was reported in the month of June, 2021 and lowest in the month of March, 2023 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh).

Table-3: Monthly average rainfall, Temperature (T), Ambient Pressure (P_{amb}), Net Radiation (Rn) and Photosynthetically Active Radiation (PAR) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh)

Year	Month	Rainfall (mm)	T_{air} (°C)	P_{amb} (kPa)	Rn (Wm^{-2})		PAR (µmolm^{-2}s^{-1})
					Day	Night	Day
1st Year (2021-22)	April	0	33.23±4.56	96.97±5.18	345.22±176.78	-70.19±18.07	885.35±544.95
	May	103.34	31.82±3.98	96.84±0.24	361.38±224.83	-50.51±18.57	848.72±626.24
	June	278.29	30.70±3.11	96.64±0.26	373.26±247.28	-25.66±10.91	746.97±569.67
	July	225.77	28.88±2.94	96.49±0.22	280.19±236.27	-19.29±11.64	552.64±501.77
	Aug.	230.87	27.18±1.76	96.72±0.20	254.03±213.46	-14.27±8.52	464.04±408.78
	Sep.	242.96	27.25±2.08	96.69±0.24	283.64±233.39	-11.22±6.15	520.37±441.59
	Oct.	68.29	24.34±4.58	97.20±0.36	436.66±277.13	-24.00±9.25	748.60±527.80
	Nov.	0	21.71±4.40	97.45±0.20	363.98±246.73	-25.75±8.80	588.96±437.33
	Dec.	8.13	18.72±4.33	97.93±0.22	556.20±717.79	-21.34±6.65	532.82±393.37
	Jan.	1.51	17.17±4.29	97.58±0.30	401.83±139.23	-26.10±13.34	666.53±422.84
	Feb.	0.25	21.07±5.24	97.37±0.24	494.34±171.27	-20.88±12.07	799.36±624.12
	March	0	26.76±6.83	96.32±0.34	614.36±224.88	-14.11±9.94	392.71±275.22
2nd Year (2022-23)	April	0	30.89±5.54	95.99±0.24	518.42±181.38	-53.72±11.67	716.61±511.76
	May	26.13	31.52±4.52	95.60±0.25	509.64±146.98	-54.21±13.07	728.82±535.67
	June	58.91	31.35±4.75	95.51±0.18	529.33±154.75	-33.10±12.73	589.57±487.46
	July	155	32.13±2.44	96.53±0.26	383.11±246.21	-.24.09±16.14	755.63±328.24
	Aug.	334.05	29.18±3.37	96.85±0.28	451.69±213.46	-37.27±11.67	890.90±432.21
	Sep.	99.18	28.64±3.13	96.19±0.27	457.51±196.37	-19.24±6.15	839.35±362.87
	Oct.	93.68	25.80±4.39	97.07±0.19	278.29±344.13	-6.44±3.85	685.53±492.35
	Nov.	0	21.43±4.78	97.13±0.18	231.58±300.14	-18.52±11.63	686.28±973.32
	Dec.	0	20.73±4.21	97.08±0.16	190.82±246.53	-3.09±2.60	533.05±882.85
	Jan.	2.02	17.34±4.94	97.21±0.28	379.49±300.80	-26.47±11.20	663.17±33.54
	Feb.	0	21.66±5.75	97.09±0.20	541.86±336.04	-41.22±10.64	786.95±43.13
	March	60.01	25.44±4.75	96.86±0.39	493.79±305.64	-40.41±20.19	762.50±43.38

Table-4: Monthly average rainfall, Temperature (T), Ambient Pressure (P_{amb}), Net Radiation (Rn) and day time Photosynthetically Active Radiation (PAR) at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

Year	Month	Rainfall (mm)	T_{air} (°C)	P_{amb} (kPa)	Rn (Wm^{-2})		PAR ($\mu mol m^{-2} s^{-1}$)
					Day	Night	Day
1st Year (2021-22)	April	7.61	30.51±5.19	96.31±0.22	327.47±174.60	-67.08±11.36	815.88±587.58
	May	140.15	28.43±3.77	95.99±0.28	374.94±268.44	-39.20±19.41	718.87±617.79
	June	140.05	28.52±2.88	95.64±0.30	335.01±476.45	-24.69±11.13	589.61±511.74
	July	342.45	28.38±2.34	95.56±0.27	280.97±222.56	-18.53±9.54	538.54±473.72
	Aug.	124.35	27.90±1.99	95.79±0.21	371.96±523.16	-20.05±8.41	608.00±492.26
	Sep.	155.93	27.84±2.40	95.89±0.17	392.51±637.29	-21.17±8.34	768.53±592.50
	Oct.	0	24.36±4.29	96.33±0.35	489.95±312.68	-47.81±12.23	694.10±632.77
	Nov.	0	16.34±4.83	96.81±0.18	389.01±100.84	-61.57±11.30	659.18±559.47
	Dec.	11.66	16.01±4.59	96.92±0.29	380.83±294.83	-62.13±11.72	502.16±420.73
	Jan.	46.67	15.94±4.60	96.78±0.30	259.08±224.92	-62.25±11.70	582.16±471.11
	Feb.	9.64	18.72±5.70	96.58±0.25	448.70±122.63	-57.49±9.81	656.35±466.98
	Mar.	0	26.76±6.83	96.32±0.34	480.62±128.93	-43.70±7.88	782.95±513.51
2nd Year (2022-23)	April	0	30.89±5.54	95.99±0.24	428.62±281.38	-31.47±10.09	716.61±511.76
	May	26.13	31.52±4.52	95.60±0.25	519.35±293.08	-32.52±11.84	728.81±535.67
	June	158.94	30.35±4.75	95.51±0.27	540.14±298.84	-30.68±11.44	589.57±487.46
	July	656.87	29.68±3.47	95.06±0.29	346.57±268.52	-25.64±16.33	794.19±473.72
	Aug.	722.72	28.16±2.59	95.09±0.26	368.96±496.38	-25.38±13.27	456.65±492.26
	Sep.	298.06	27.84±2.40	95.78±0.13	385.01±237.29	-29.14±10.39	595.65±592.50
	Oct.	108.91	26.90±3.12	96.67±0.22	436.83±296.75	-39.66±22.05	587.53±368.44
	Nov.	0	15.98±5.06	96.52±0.15	353.47±158.32	-65.42±19.36	597.66±366.37
	Dec.	0	15.43±5.27	96.03±0.21	346.91±268.55	-58.44±16.79	566.16±420.73
	Jan.	0	17.16±5.88	96.678±0.26	254.77±208.13	-36.65±21.84	629.28±460.19
	Feb.	0	21.01±6.52	96.48±0.21	347.07±231.32	-43.25±30.01	855.17±505.41
	March	66.52	24.91±4.92	96.09±0.36	310.34±238.72	-42.74±29.53	910.91±606.86

Table-5: Monthly average relative humidity (RH), Wind speed and mixing ration (U*) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

Year	Month	Khatpura			Sonhat		
		RH (%)	Wind Speed (ms^{-1})	U*	RH (%)	Wind Speed (ms^{-1})	U*
1st Year (2021-22)	April	16.35 ±8.19	1.44±0.98	0.33±0.22	20.83±13.57	2.15±1.25	0.31±0.25
	May	40.70±18.16	1.69±1.0	0.41±0.24	53.67±19.93	2.06±1.23	0.31±0.22
	June	62.94±14.16	1.27±0.76	0.41±0.19	72.93±9.13	2.25±0.95	0.31±0.17
	July	67.88±14.04	1.12±0.69	0.35±0.19	79.75±11.61	2.12±1.0	0.28±0.16
	Aug.	78.87±6.27	1.07±0.72	0.34±0.18	78.61±9.73	1.97±1.15	0.26±0.17
	Sep.	84.06±6.94	0.51±0.43	0.17±0.12	78.64±10.29	1.91±1.12	0.24±0.15
	Oct.	60.28±13.22	0.62±0.57	0.21±0.11	73.01±17.43	1.43±0.87	0.19±0.15
	Nov.	54.63±16.87	0.76±0.62	0.22±0.13	65.58±18.26	1.32±0.66	0.15±0.11
	Dec.	53.38±18.85	0.82±0.54	0.18±0.16	63.57±18.55	1.24±0.68	0.16±0.12
	Jan.	61.25±16.41	0.81±0.50	0.20±0.16	54.75±20.46	1.70±0.88	0.23±0.15
	Feb.	44.24±14.54	0.85±0.59	0.20±0.18	49.16±20.98	1.93±1.18	0.26±0.22
	Mar.	20.11±14.24	1.26±0.91	0.28±0.22	34.31±19.73	2.05±1.24	0.28±0.25
2nd Year (2022-23)	April	09.74±4.42	1.68±0.98	0.37±0.22	14.71±8.46	2.20±1.27	0.40±0.26
	May	27.57±11.31	1.73±0.99	0.44±0.23	35.55±16.21	2.41±1.30	0.37±0.24
	June	34.15±16.58	2.22±0.81	0.58±0.18	43.20±17.23	2.12±1.05	0.30±0.19
	July	76.24±8.90	1.25±0.41	0.36±0.18	71.34±12.74	2.46±1.33	0.31±0.18
	Aug.	75.89±10.07	1.18±0.54	0.31±0.20	77.37±0.23	2.17±1.28	0.30±0.18
	Sep.	75.20±11.60	0.93±0.48	0.27±0.18	79.82±10.61	1.97±1.11	0.27±0.16
	Oct.	55.23±15.61	0.73±0.42	0.15±0.13	77.73±11.73	1.65±0.91	0.25±0.16
	Nov.	48.61 ±14.11	0.70±0.35	0.14±0.11	68.67±16.43	1.05±0.77	0.24±0.16

	Dec.	53.32 ± 14.17	0.73±0.43	0.16±0.13	59.35±12.33	0.96±0.60	0.23±0.17
	Jan.	54.04 ± 14.71	0.82 ± 0.48	0.20±0.16	40.98±19.13	1.69 ± 0.84	0.18±0.13
	Feb.	36.88 ± 0.14	0.88 ±0.49	0.22±0.17	20.79±11.22	1.18 ±1.42	0.35±0.22
	March	38.77 ± 14.07	1.15 ±0.60	0.31±0.17	57.93±11.76	1.47 ±0.55	0.28±0.09

Table-6: Monthly average day time Sensible Heat Flux (H), Latent Heat Flux (LE) and Energy Balance Closure (EBC) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

Year	**Month**	**Khatpura**			**Sonhat**		
		H (Wm^{-2})	**LE (Wm^{-2})**	**EB (Wm^{-2})**	**H (Wm^{-2})**	**LE (Wm^{-2})**	**EBC (Wm^{-2})**
1st Year (2021-22)	April	175.07±7.71	25.00±1.06	200.07±4.54	49.16±2.42	185.56±6.65	234.71±8.39
	May	146.30±3.97	110.49±3.13	256.84±5.49	105.81±3.39	147.69±5.45	253.50±6.85
	June	105.41±4.58	200.56±8.71	305.98±13.28	66.32±2.87	188.58±5.03	254.90±6.98
	July	68.43±2.76	256.26±5.89	271.34±8.33	51.57±2.03	177.76±6.60	229.32±7.78
	Aug.	45.41±3.03	132.95±8.22	178.36±10.52	40.24±2.69	162.19±9.35	202.43±10.56
	Sep.	63.44±13.42	144.59±19.60	208.03±32.25	51.63±2.56	177.86±8.25	229.49±9.77
	Oct.	76.94±5.58	83.87±9.04	160.81±14.17	52.95±1.85	169.99±5.39	222.94±6.51
	Nov.	65.13±6.28	82.20±7.99	147.33±13.15	57.76±2.29	111.43±4.64	169.19±610
	Dec.	78.59±4.22	90.56±3.31	169.15±6.56	75.30±13	67.84±3.08	143.14±5.35
	Jan.	104.66±3.19	82.72±2.48	187.38±4.84	83.01±3.17	66.19±3.42	149.20±5.45
	Feb.	122.87±4.54	90.84±3.25	213.72±6.90	126.85±3.95	76.71±3.09	203.56±6.21
	March	158.93±4.37	51.77±2.09	210.71±5.34	163.96±4.17	47.07±2.76	211.03±5.39
2nd Year (2022-23)	April	177.44±7.71	24.41±1.06	201.84±8.77	173.49±4.37	29.31±2.24	202.80±4.99
	May	180.56±5.88	53.621±3.30	234.18±7.03	154.98±4.38	60.20±4.07	215.18±6.07
	June	101.18±7.83	193.78±9.47	294.96±6.44	96.53±5.66	144.70±6.74	157.59±9.57
	July	59.65±2.77	136.58±5.64	292.14±8.05	68.39±2.24	184.54±3.99	252.94±5.51
	Aug.	56.29±2.69	231.91±6.34	288.20±8.42	55.80±2.30	192.36±5.63	248.15±7.36
	Sep.	50.34±2.06	251.85±6.57	302.18±7.97	52.35±1.99	185.34±5.11	237.69±6.50
	Oct.	38.46±1.43	234.46±6.41	272.92±7.09	49.16±2.42	185.56±6.65	234.71±8.39
	Nov.	46.28±1.6	165.73±4.72	145.05±4.96	45.51±13.99	119.85±7.29	165.35±10.64
	Dec.	53.35±2.55	134.97±4.17	188.32±6.01	99.79±6.39	89.60±5.81	188.70±10.17
	Jan.	50.21±3.24	121.39±4.04	171.60±6.46	119.82±4.13	58.63±2.72	178.44±5.82
	Feb.	128.07±3.81	94.39±2.49	222.46±5.76	90.66±6.30	63.79±3.33	154.45±7.86
	March	147.48±4.38	65.44±1.99	212.93±5.45	86.64±6.30	45.75±3.56	132.39±6.53

Table-7: Monthly mean Net Ecosystem Exchange (NEE), Gross Primary Productivity (GPP) and Ecosystem respiration (R_{eco}) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

Year	**Month**	**Khatpura**			**Sonhat**		
		NEE (µmolm^{-2}s^{-1})	**GPP (µmolm^{-2}s^{-1})**	**R (µmolm^{-2}s^{-1})**	**NEE (µmolm^{-2}s^{-1})**	**GPP (µmolm^{-2}s^{-1})**	**R_{eco} (µmolm^{-2}s^{-1})**
1st Year (2021-22)	April	2.14±0.15	4.46±0.25	6.57±0.22	2.08±0.17	4.59±0.09	6.67±0.26
	May	1.39±0.11	5.83±0.14	4.44±0.11	1.28±0.09	5.04±0.24	6.32±0.22
	June	1.17±0.38	7.45±0.78	8.62±0.79	1.13±0.33	6.18±0.49	7.31±0.65
	July	-1.28±0.68	9.74±0.58	8.76±0.64	-0.75±0.45	6.41±0.97	6.87±0.72
	Aug.	-2.11±0.27	10.05±0.32	7.94±0.28	-1.33±0.40	6.45±0.74	5.12±0.55
	Sep.	-2.02±0.15	9.27±1.26	7.25±1.22	-2.37±1.15	7.54±2.67	5.17±2.38
	Oct.	-1.83±1.05	9.04±1.07	8.21±1.09	-1.87±0.15	8.38±0.37	6.51±0.35
	Nov.	-1.30±0.87	9.38±0.82	8.08±0.76	-0.79±0.08	8.23±0.80	7.43±0.81
	Dec.	-0.96±0.17	7.88±0.46	6.92±0.38	-0.87±0.11	8.05±0.43	7.18±1.43
	Jan.	-0.93±0.12	6.58±0.35	5.64±0.36	-0.89±0.10	8.06±0.58	7.17±0.57

	Feb.	-0.90±0.45	5.31±0.74	4.19±0.74	-0.58±0.05	6.52±0.52	5.94±0.52
	March	1.19±0.33	4.56±0.45	5.75±0.34	1.42±0.11	4.93±0.71	6.35±1.07
2nd Year (2022-23)	April	2.02±0.18	4.35±0.32	6.37±0.33	2.18±0.19	4.47±0.11	6.65±0.30
	May	1.12±0.22	4.19±0.40	5.31±0.45	1.28±0.49	4.32±1.91	5.60±1.93
	June	-0.11±0.23	7.44±0.42	7.33±0.44	1.70±0.22	6.78±2.13	8.49±2.09
	July	-1.06±0.13	6.29±0.19	5.23±0.32	-1.63±0.33	8.20±0.49	6.57±0.34
	Aug.	-2.06±0.34	8.79±0.52	6.72±0.66	-1.74±0.23	8.13±0.51	6.64±0.43
	Sep.	-1.52±0.18	7.84±0.42	6.32±0.42	-2.07±0.22	8.51±0.33	6.44±0.46
	Oct.	-1.33±0.16	7.14±0.25	6.51±0.39	-1.91±.0.22	7.76±0.31	5.85±0.26
	Nov.	-0.62 ±0.12	7.52±0.81	6.91±0.80	-0.81±0.09	8.05±0.77	7.24±0.76
	Dec.	-0.88 ± 0.23	7.35±0.53	6.86±0.49	-0.79±0.26	7.56±0.60	6.75±0.16
	Jan.	-0.98 ± 0.01	6.53 ± 0.77	5.55±0.08	-1.03 ± 0.15	7.74 ± 0.93	6.71±0.39
	Feb.	-1.04 ± 0.14	5.67 ±0.89	4.63±0.05	-0.82 ± 0.33	6.65 ±0.83	5.83±058
	March	0.38 ± 0.24	4.97 ±1.08	5.35±0.01	1.62 ± 0.40	5.03 ±0.97	6.65±0.17

3.4. Ecosystem Carbon Fluxes

The mean net ecosystem exchange (NEE) of CO_2 ranged from -2.11 to 2.14 µmol $m^{-2} s^{-1}$ at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from -2.37 to 2.08 µmol$m^{-2}s^{-1}$ at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Table 7). The annual mean NEE was -0.45 and -0.47 µmol m^{-2} s^{-1} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh), respectively, for the 1st year and 2nd year observation period. Similarly, it was recorded as -0.30 and -0.34 µmol $m^{-2} s^{-1}$, respectively, for the 1st year and 2nd year indicating the net sink of carbon to the atmosphere over study period. The mean NEE was recorded lower in the wet seasons (-0.57 and -0.73 in µmol $m^{-2} s^{-1}$) than dry season (-0.37 and -0.29 µmol m^{-2} s^{-1}) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) Similarly, it was recorded lower (-0.41 and -0.49 µmol m^{-2} s^{-1}) in wet season than the dry season (-0.20 and -0.25 µmol $m^{-2} s^{-1}$) in year 2022 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Table 8). At both the forests, lower NEE in wet season indicates higher CO_2 uptake during this season.

In the wet season, more moisture is available in the ecosystem with enough sunshine, which leads to higher energy flux and evapotranspiration. The stomatal openings are responsible for carbon fixation via photosynthesis as well as for water loss through transpiration (Grachev *et al.*, 2020). The study sites experiences monsoon rainfall during July-September months. The higher GPP observed during the monsoon season can be attributed to the favourable environmental conditions (i.e., temperature, moisture, and LAI) (Ahongshangbam *et al*., 2016; Srinet *et al.*, 2022). A significant correlation between temperature as well as precipitation and GPP values of two subtropical forests was reported by Srinet *el al.* (2022) in North West Himalayan foot hills. The rate of plant metabolism is regulated by temperature, which in turn determines the amount of photosynthesis (Boisvenue and Running, 2006).

The monthly loss and gain of CO_2 in the atmosphere are shown in the Figure 4. The CO_2 uptake from the atmosphere has been reported from the month of July to February continuously at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). But the CO_2 uptake was also recorded in the month of May at Sonhat Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Figure 4). The highest CO_2 uptake was reported in the month of August 2021 (2.49 t C ha^{-1}) followed by August 2022 (2.38 t C ha^{-1}) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh). Similarly, the highest CO_2 uptake at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) was reported in the month of September 2021(2.70 t C ha^{-1}) followed by September 2022 (2.39 t C ha^{-1}). This shows that the highest CO_2 uptake from the atmosphere was during post monsoon season. Similar trends were observed by Singh *et al.* (2019) for the Chir pine forest in western Himalaya, Sarma *et al*., (2019) for the tropical forest of northeast India and Watham *et al*., (2020) for subtropical tropical forests in Western Himalaya. Favourable climatic conditions with clear sky, high leaf area index (LAI), adequate water for photosynthesis and reduced R_{eco} with low temperature lead to maximum CO_2 in this period.

Availability of light and meteorological conditions influence photosynthesis and CO_2 uptake (Gu *et* *al*., 1999; Law *et al*., 2002; Watham *et al*., 2017). During post-monsoon season, the luxuriant herbaceous growth in the understorey has also added to higher carbon updates (Watham *et al*., 2021).

The mean annual ecosystem respiration (R_{eco}) was 6.86 and 5.92 µmol m^{-2} s^{-1} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and 6.39 and 6.51 µmol m^{-2} s^{-1} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) in the 1st year and 2nd year respectively (Table 8). The monthly mean R_{eco} ranged from 4.19 to 8.76 µmol m^{-2} s^{-1} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 5.12 to 8.49 µmol m^{-2} s^{-1} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Table 7). The mean R_{eco} was higher in the wet season than the dry season at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) during the study period. But, it was higher in dry seson at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Table 8). It may be because of seasonal variations in environmental conditions.

Table-8: Seasonal and interannual variation of Net Ecosystem Exchange (NEE), Gross Primary Productivity (GPP) and Ecosystem respiration (R_{eco}) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

Site	Year	Variable	Season		Annual
			Dry	Wet	
Khatpura	1st Year (2021-22)	NEE (µmol$m^{-2}s^{-1}$)	-0.37±0.42	-0.57±0.69	-0.45±0.43
		GPP (µmol$m^{-2}s^{-1}$)	6.74±0.60	8.47±0.71	7.46±0.60
		R_{eco} (µmol$m^{-2}s^{-1}$)	6.48±0.41	7.40±70	6.86±0.45
	2nd Year (2022-23)	NEE (µmol$m^{-2}s^{-1}$)	-0.29±0.33	-0.73±0.50	-0.47±0.34
		GPP (µmol$m^{-2}s^{-1}$)	6.27±0.43	7.13±0.54	6.70±0.41
		R_{eco} (µmol$m^{-2}s^{-1}$)	5.90±0.22	5.96±0.50	5.92±0.27
Sonhat	1st Year (2021-22)	NEE (µmol$m^{-2}s^{-1}$)	-0.20±0.55	-0.41±0.63	-0.30±0.41
		GPP (µmol$m^{-2}s^{-1}$)	6.95±0.63	6.32±0.36	6.82±0.36
		R_{eco} (µmol$m^{-2}s^{-1}$)	6.75±0.20	6.16±0.39	6.39±0.26
	2nd Year (2022-23)	NEE (µmol$m^{-2}s^{-1}$)	-0.25±0.56	-0.49±0.73	-0.34±0.45
		GPP (µmol$m^{-2}s^{-1}$)	6.81±0.51	7.44±0.49	7.21±0.32
		R_{eco} (µmol$m^{-2}s^{-1}$)	6.56±0.20	6.49±0.59	6.51±0.28

The gross primary productivity (GPP) ranged from 4.19 to 10.05 µmol m^{-2} s^{-1}) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and from 4.32 to 8.51 µmol m^{-2} s^{-1}) at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) during the study period (Table 7). The mean annual GPP was 7.46 and 6.70 µmol m^{-2} s^{-1} at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and 6.82 and 7.21 µmol m^{-2} s^{-1} at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) respectively in the 1st year and 2nd year. The mean GPPs in the wet seasons were higher than in the wet season than the dry season at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh). The mean GPP was also higher in the wet season than the dry season during the 2nd year at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh), but it was higher in dry season during the 1st year (Table 8). This may be due to comparatively high rainfall in the months of September and October that year. The higher GPP than the R_{eco} recorded in both the season indicates that forests act as carbon sink. The higher GPP during August to October (post monsoon season) was recorded at both the forests (Table 7). During this period, leaves on trees are rapidly expanding, causing a concomitant increase in leaf area and photosynthesis., the mean GPP was recorded comparatively lesser during the month of March to May than the other months of the year at both the sites. This is the period when deciduous trees start senescence.

Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) act as source of carbon from March to June (Figure 2). The highest CO_2 emission was recorded in April month at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). The highest CO_2 emission at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) was 2.44 t/ha in the month of April 2021 and at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) was 2.51t/ha in the month of April 2022. The forests act as carbon source in this period as senescence of most of the tree species takes place during March and April. Incidence of the forest fires was also reported which also contributed in the emission of carbon from the forests. The flushing of new leaves begins in the month of late April to May. Therefore, low leaf area during April to June reduces GPP lowering the net carbon uptake.

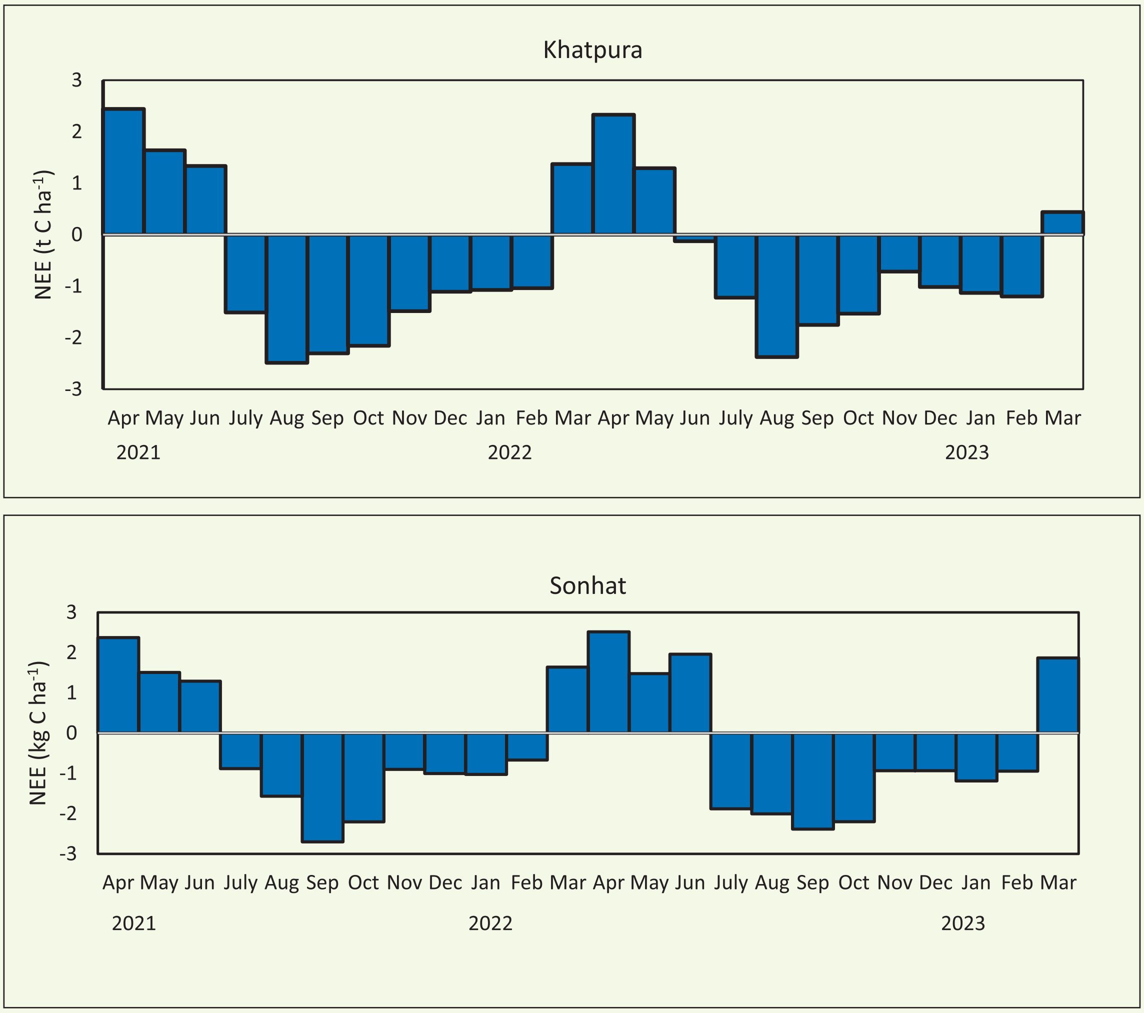


Fig. 4.: Monthly time series of mean Net Ecosystem CO_2 Exchange (NEE) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

Beside this, anthropogenic forest fire during March-April could be another reason for higher CO_2 emission during this period. Visual observation of forest fire near the EC flux tower during the study period indicates that the forest fire is one of the major reasons for carbon emission in these forests. Nearly 4% of the nation's forest cover has been determined to be extremely fire prone, while 6% of it is categorized as very highly fire prone (FSI, 2019). About 54.40% of India's forests are subjected to infrequent fires, 7.49% to moderately frequent fires, and 2.40% to high incidence levels, while 35.71% of India's forests are yet to be exposed to significant fires. Every year, precious forest resources, including carbon contained in biomass, are lost due to forest fires, which have a negative influence on the functioning and services of forest ecosystems (FSI, 2023). Therefore, more effective and ecological approach is required to prevent the forest fire. Participatory forest management by forest department personnel and locals could be used. Fuel load management, including controlled fire, fire line construction, and fire-prone region mapping, are key elements of fire hazard reduction.

The interannual variation in NEE, GPP and R_{eco} could be due to the monthly variation in meteorological condition. Similar observation was reported from the natural and planted forests in Western Himalayan foothills (Watham *et al.*, 2020). The mean carbon flux is influenced by the number of rainy days, available PAR and VPD which results in variation in carbon budgets at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). During

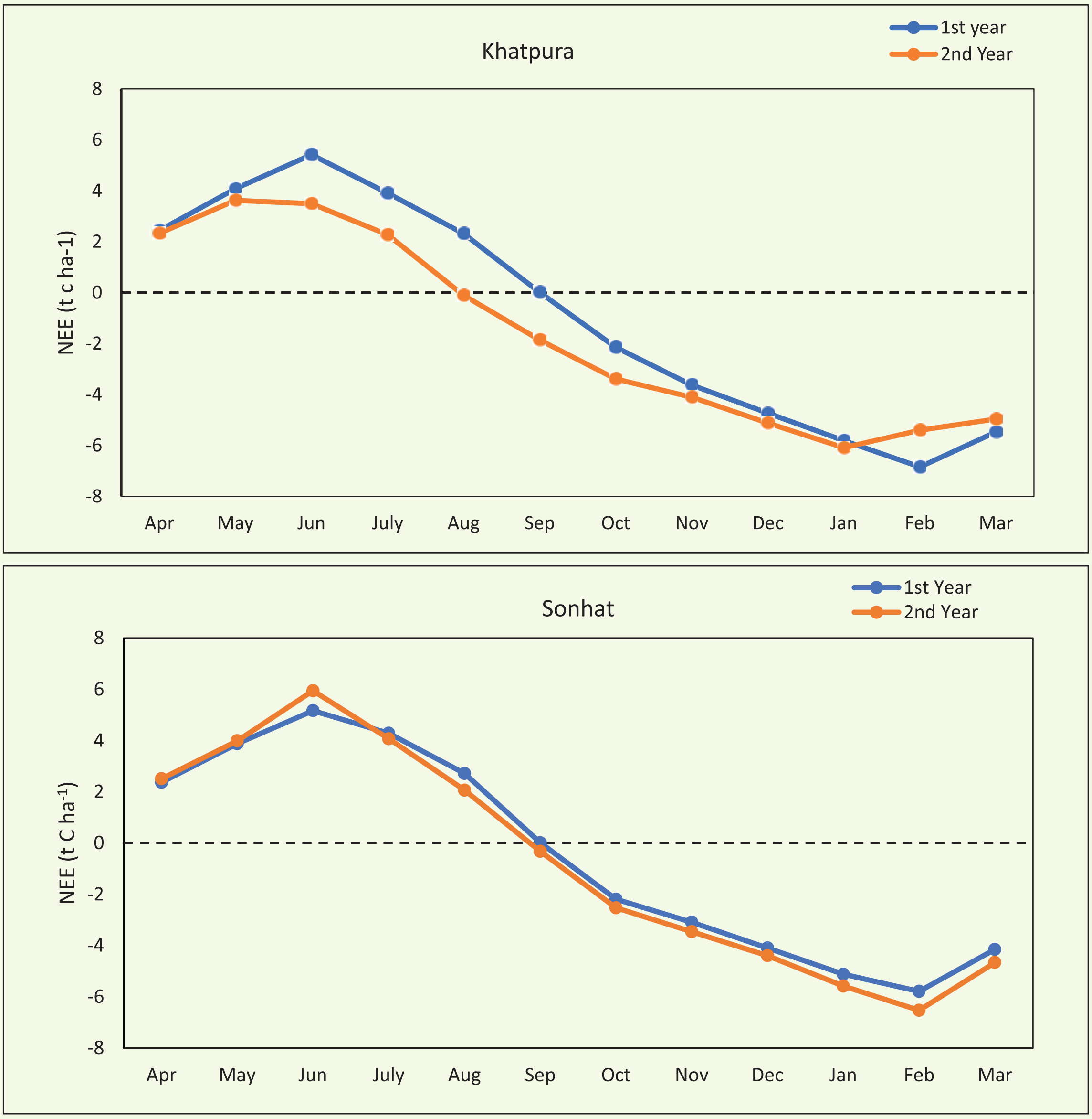


Fig. 5.: Time series of cumulative net ecosystem CO_2 exchange (NEE) during 1st year (April 2021-March 2022) and 2nd year (April 2022- March 2023) between the canopy and atmosphere at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

rainy days the GPP is reduced due to lower PAR and RE was relatively increased due to increase in heterotrophic respiration, thus influence the resultant NEE (Watham *et al.*, 2020). It is well established that the amount of rain controls the soil moisture availability and thereby affects the soil respiration. Soil respiration increases with increased precipitation or prolonged wet season and decreases with decreased precipitation or drought (Meir *et al.*, 2015; Liu *et al.*, 2016).

The growing seasons of the plants in different parts of the world~~s~~ is regulated by the climatic factors (Nandy *et al.*, 2021). Temperature is one of the key drivers for plant photosynthesis which influence ecosystem productivity and terrestrial CO_2 sink dynamics (Running *et al.*, 2004). Suitable warm and humid climatic condition could be reason behind the higher productivity (Srinet *et al.*, 2022). The Leaf Area Index (LAI) also increases with the optimum temperature and humidity which in turn influence the carbon dynamics. Contrast to the present study, peak CO_2 concentration during February–March and lowest during monsoon and post-monsoon was reported from the Cape Rama (Tiwari *et al.*, 2013). This difference could be because of the difference in site condition and to some extent due to temperature. The location of the carbon flux tower in Cape Rama is situated in a maritime site located on flat rocky terrain overlooking the sea, and without any vegetation and few hundred metres away from sparse habitation (Tiwari *et al.*, 2013). Therefore, the eddy covariance measurement of Cape Rama is mostly influenced by long-distance transport and the air sample collected from June to September represents southern hemisphere oceanic air mass (Bhattacharya *et al.*, 2009).

3.5. Cumulative net ecosystem CO_2 exchange (NEE)

The cumulative net ecosystem CO_2 exchanges (NEE) are shown in the Figure 3. The net CO_2 uptake from the atmosphere was 5.47 and 4.96 t C ha^{-1} respectively during the 1st year and 2nd year at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh). It was 4.15 and 4.66 t C ha^{-1} respectively during the 1st year and 2nd year at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Figure 5). The cumulative CO_2 uptake recorded in the present study are comparable with value reported by Du *et al.*, (2022) from the forests on Tibetan Plateau (5.4 t C ha^{-1}) and Verlinden *et al.*, (2013) from poplar plantation in Belgium. The net CO_2 uptake values reported in the present study was much higher than Canadian Boreal forests (2.5 t C ha^{-1}) reported by Sun *et al.*, (2008).

The two years cumulative NEE data shows that both forests under the present study are playing their crucial role in mitigation of climate change by abating atmospheric carbon added by anthropogenic activities. This type of information encourages the forest conservators for more attention towards the conservation of the existing natural forests. The policy makers may extract a fair idea from such type of information (NEE) on carbon absorption potentiality of the forests and help in asserting whether the conservation of these existing forests can meet the regional/ national carbon sequestration targets or how much area is needed to be afforested to achieve the targets. India's NDC has targeted to sink 2.5-3.0 Gt C from the atmosphere through additional forests and forest cover by 2030. The findings of the present study may help the forest managers in forest carbon assessments and afforestation programs. One can validate the MRV of other inventory carbon sink projects in similar forest types by comparing the NEE recorded values of the present study. For example, Forest Survey of India is accounting forest carbon fluxes by conducting inventory of GHG fluxes in land use, land-use change, and forestry (LULUCF) sector following IPCC good practice guidance. The values reported in the present study may help in assessing carbon emission factors for these forest types.

3.6. Diurnal cycle of net ecosystem exchange (NEE)

The Figure 4 shows that the diurnal variation in net ecosystem exchange **(**NEE) was during the dry and wet seasons. This variation most likely reflects the daytime carbon uptake and night time carbon emission to the atmosphere. The NEE was converted from a positive value (representing carbon emission) to a negative value (representing carbon absorption) in the morning. The carbon uptake reached peak during before noon hours (1000–1100 hrs) in both wet and dry season, and then started to diminish at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). In the evening (approximately 1800 hrs), the NEE changed from a negative value to a positive value indicating carbon emission to the atmosphere (Figure 6). The highest mean hourly NEE was recorded 10.09 and 10.45 µmol m^{-2} s^{-1} during wet season respectively in the year 2021 and 2022 at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and during the dry season it was 5.06 and 5.89 µmol m^{-2} s^{-1}. Similarly, highest mean hourly NEE were 9.34 and 10.09 µmol m^{-2} s^{-1} during wet season respectively in the year 2021 and 2022 at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). During dry season, the highest mean hourly NEE were 6.40 and 7.25 µmol m^{-2} s^{-1}.

The highest carbon uptake before the noon hours during wet season indicates that the daily NEE is suppressed around noon. This could be because of photosynthetic depression at high temperatures, as well as stomatal closure at high photosynthetic photon flux density (PPFD) levels, the carbon assimilation was severely restricted at noon and during the early afternoon (Fu *et al.*, 2014). The midday suppression of transpiration and CO_2 assimilation rates at hot and humid environment is a common phenomenon in tropics (Tenhunen *et al.*, 1984, Küppers *et al.*, 1986, Pathre *et al.*, 1998). The same phenomenon also occurs in tropical rainforest trees, as indicated by a marked decrease in photosynthetic rate and stomatal conductance during midday and afternoon (Huc *et al.*, 1994; Zotz *et al.*, 1995, Ishida *et al.*, 1999).

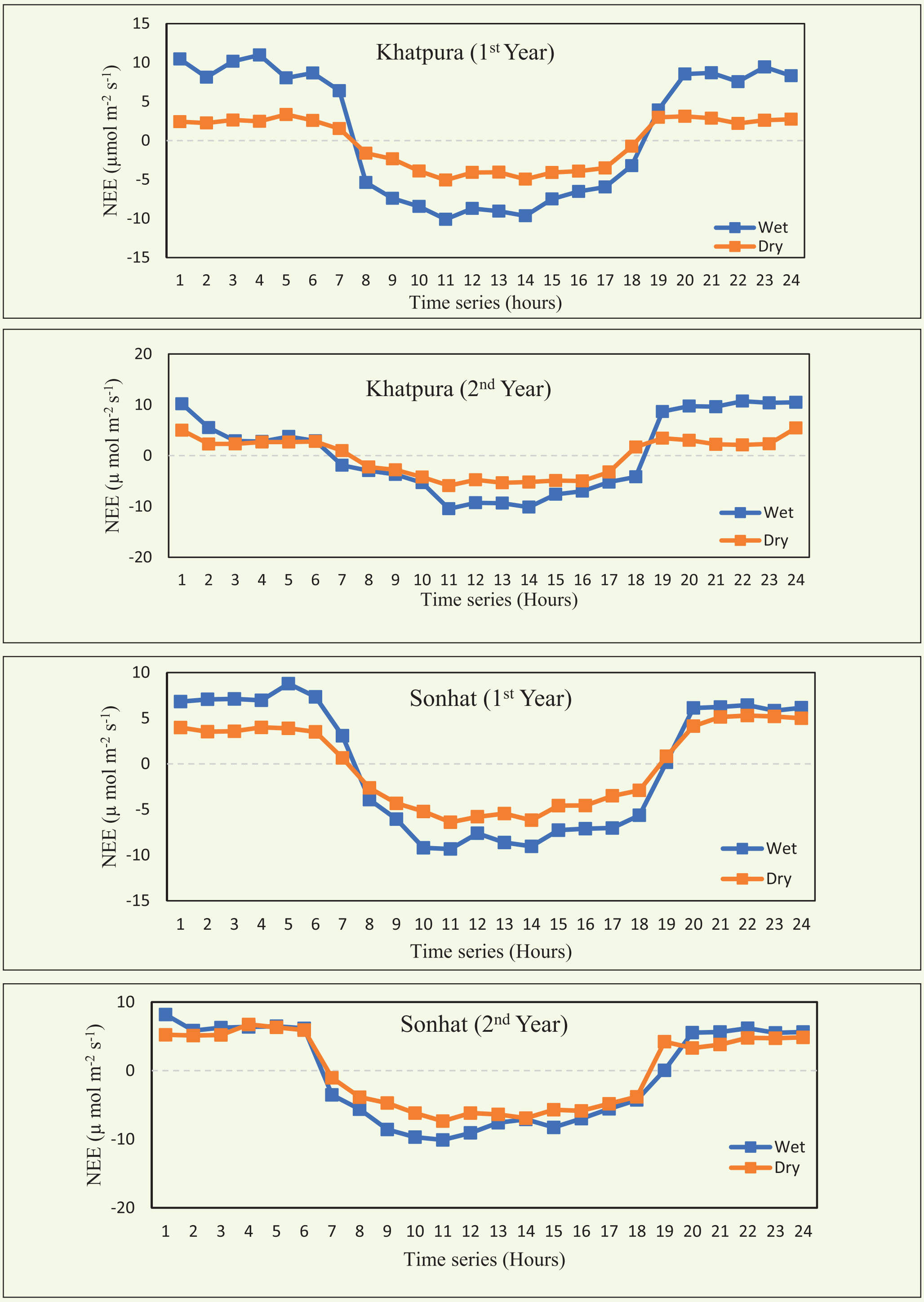


Fig. 6.: Average diurnal cycle of net ecosystem CO_2 exchange (NEE) in wet and dry seasons during 1st year (April 2021-March 2022) and 2nd year (April 2022- March 2023) between the canopy and atmosphere at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

3.7. Relationship of NEE with environmental parameters

In this study, it has been observed that air temperature (T_a), vapour pressure deficit (VPD) and photosynthetically active radiation (PAR) affect the net C uptake or NEE. Monthly average NEE was strongly corelated with the T_a at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) ($R^2=0.34$, $P<0.01$) and moderately corelated at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) ($R^2=0.28$, $P<0.05$). Similarly, NEE was moderately corelated ($R^2=0.31$) with PAR at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and weakly ($R^2=0.24$) corelated at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (Figure 7). Temperature affected both the physiology and phenology of plants, which in turn determined the carbon uptake and release. The reason behind the weaker or moderate relationship of T_a and PAR with NEE may be due to the lower leaf area or LAI during dry summer period (mid April to June). As most of the trees remain leafless or start leaf flushing during this season resulting into low NEE or carbon uptake.

An important environmental factor for understanding ecophysiological activities of plants is the vapour pressure deficit (VPD), which is the difference between the water vapour pressure at saturation and the actual water vapour pressure for a given temperature (Rawson *et al*., 1977). Changes in VPD are crucial for the functioning of terrestrial ecosystems (Yuan *et al*., 2019). To determine the control of VPD on net ecosystem exchange, VPD values were plotted against the NEE (Figure 7). A strong and significant ($P<0.01$) relationship was recorded between NEE and VPD at both Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) ($R^2=0.80$) and Southern Mixed Deciduous Forest, Sonhat

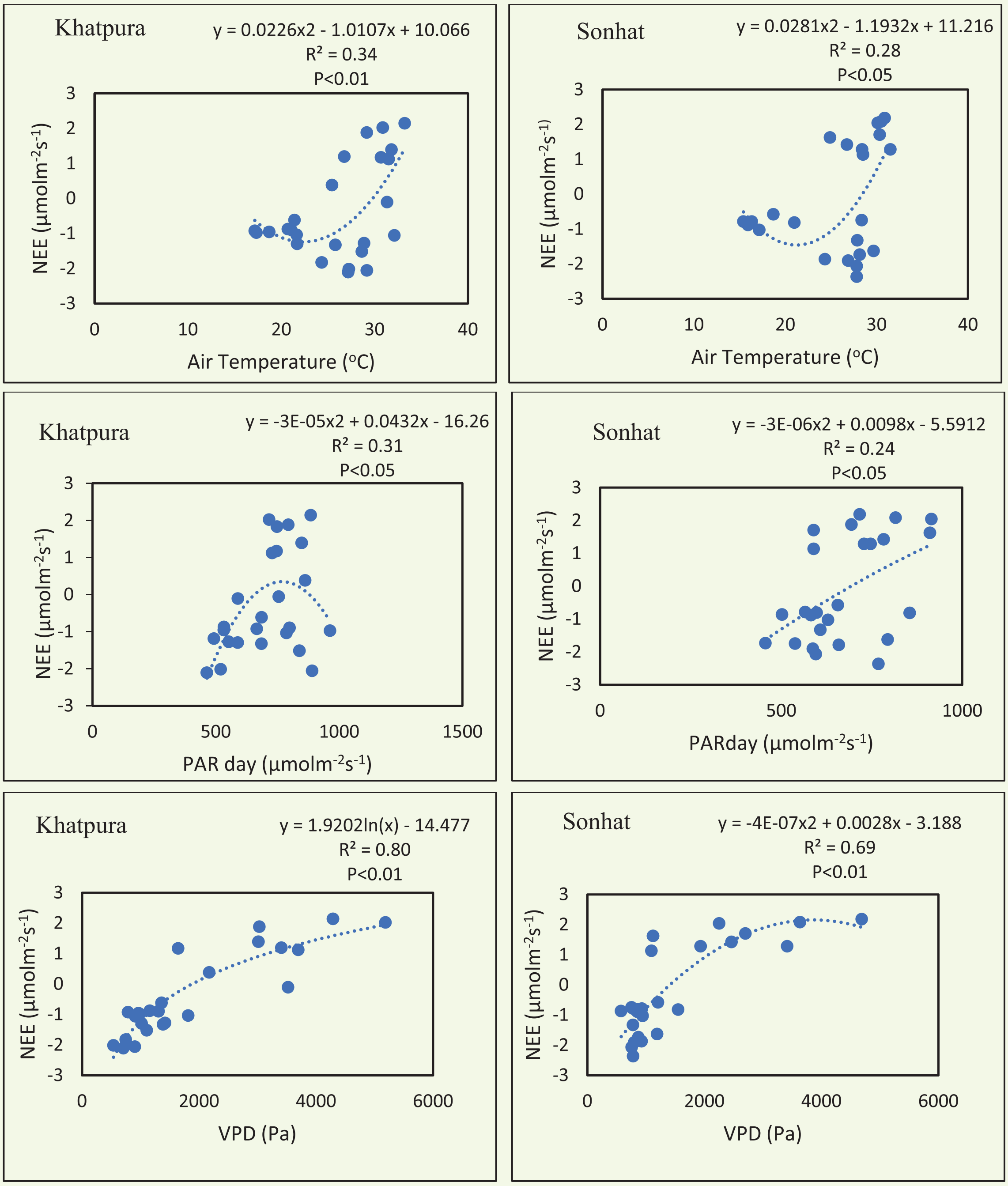


Fig. 7.: Relationship of Net Ecosystem Exchange (NEE) with air temperature (Ta), photosynthetically active radiation (PAR) and vapour pressure deficit (VPD) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

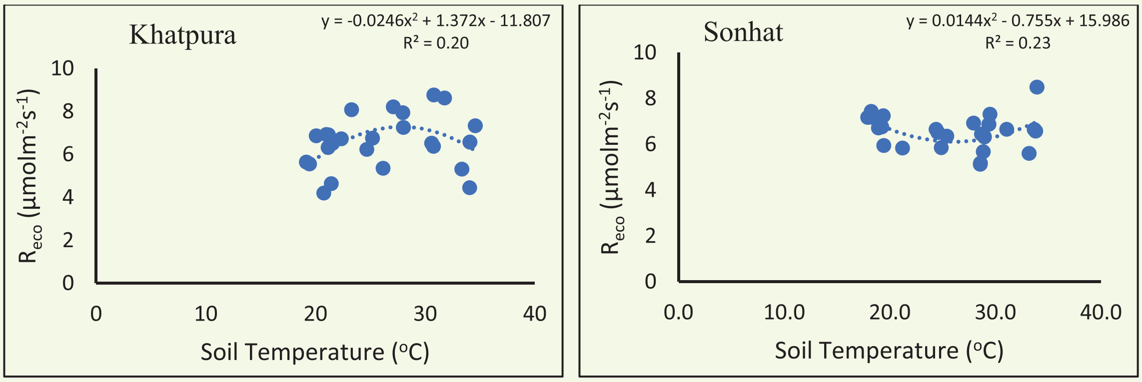


Fig. 8.: Relationship of Ecosystem Respiration (R_{eco}) with average soil temperature (°C) at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh)

(Chhattisgarh) (R^2=0.69). Similar relationship was also reported from natural and plantation forests in western Himalayan Region (Watham *et al.*, 2020). VPD influences stomatal movements (Sulman *et al.,* 2016), water and nutrient uptake (Leuschner 2002, Jiao *et al.*, 2022). A 13 years reaserch data from a forest in south central Indiana, USA shows that increasing VPD under warm climatic condition could reduce forest CO_2 uptake regardless of changes in soil water content (Sulman *et al.*, 2016). Researchers reported that NEE responses to the combine effects of Ta, VPD and PAR on its two components: respiration and gross productivity. Generally, environmental conditions with low VPD and temperature close to the photosynthetic thermal optimum creats a favourable condition for photosynthesis increasing the Net C uptake from the atmosphere (Messori *et al.*, 2019).

Ecosystem respiration is a key process in the carbon cycle of terrestrial ecosystems. Ecosystem respiration (R_{eco}) is the quantity of CO_2 released back into the atmosphere by autotrophic and heterotrophic respiration, and it accounts for a significant percentage of the terrestrial GPP and carbon cycle (Kirschbaum *et al.,* 2001). Soil temperature is one of the dominant controlling factor of ecosystem respiration (Gudasz *et al.,* 2021). In the study average soil tempertrure was moderately co-related with the ecosystem respiration at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) (R^2=0.20) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) (R^2=0.23) Figure 8. NEE is the difference between GPP and Reco. Any change in R_{eco} directly influence NEE. Therefore, relationship between R_{eco} and soil temperature indicates that change in soil temperature impacts NEE.

3.8. Scope for Eddy Flux Network

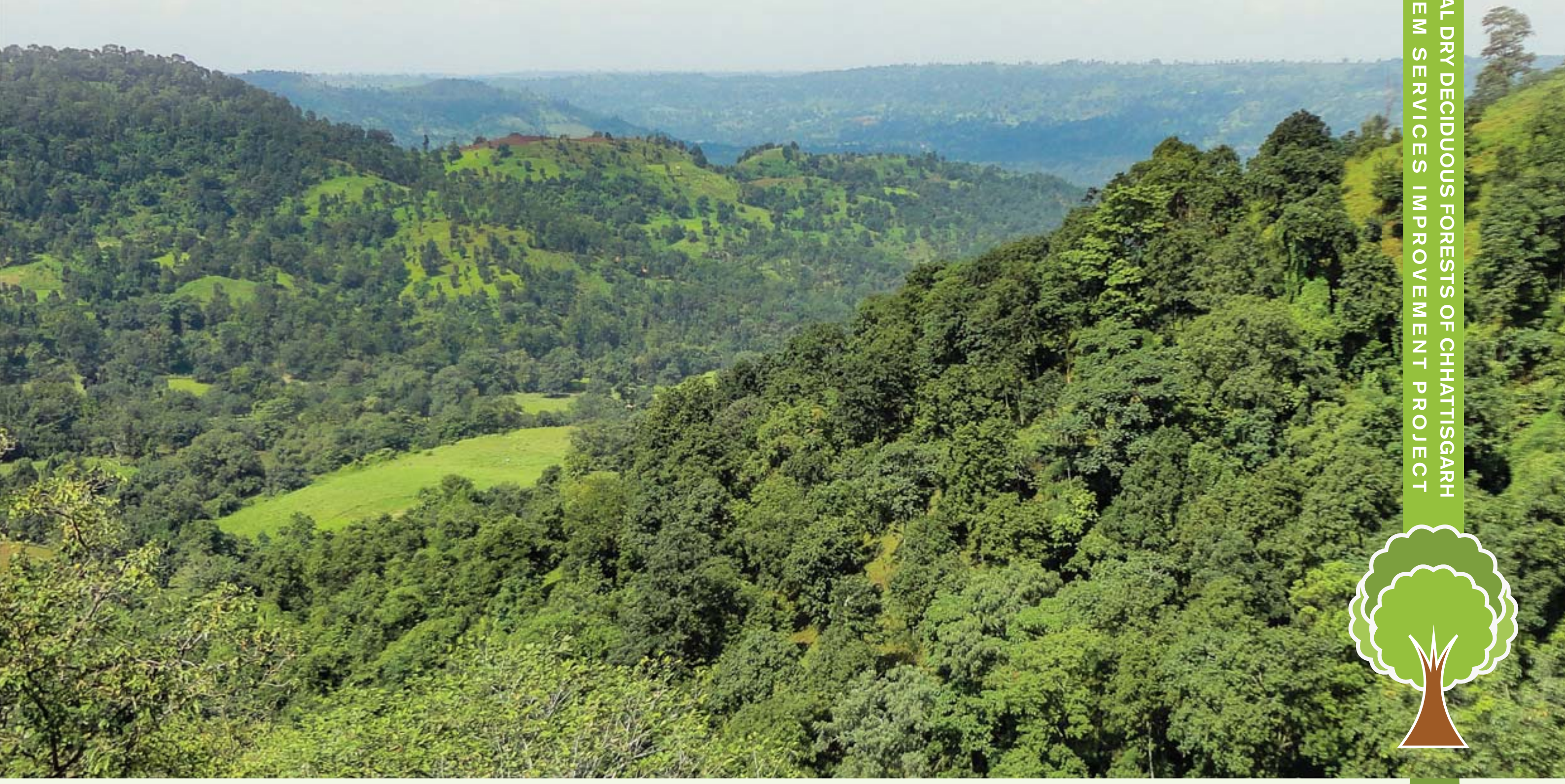
India has 14 physiographic zones with diverse and distinctive forest ecosystems including tropical rainforests, tropical deciduous, temperate forests, alpine vegetation, and coastal wetalnds. These ecosystems have a big impact on the local and global environment. A direct measurement of ecysytem fluxes (.e.g., carbon flux, water flux, GHG fluxes, energy flux, etc.) is very important for the understanding of source/ sink nature of these forest ecosystems, and their spatial and temporal variations. Looking at the global scenario, India has very little representation in the global carbon flux networks. The eddy towers can provide information specific to a single ecosystem type or condition. For understanding the consequences of global environmental change and its mitigation in diverse country like India require an integrated national effort of comprehensive long-term data collection, synthesis, and interpretation. Some Government organization such as NRSC, IIRS, IITM, ICFRE, etc. has established carbon flux towers in different parts of the country. There is a need to develop a mechanism for networking of the already installed eddy covariance-based carbon flux towers in the form of Indo Flux for comprehensive observation, sharing of the data and results for further preparation of the country level report on the carbon fluxes of the forests. Subsequently networking of carbon flux towers can also be done with Asia Flux.

04

Conclusion

Northern mixed deciduous forest of Madya Pradesh and Southern mixed deciduous forest of Chhattisgarh act as net carbon sink with a net carbon uptake of 4.96 - 5.47 t C ha^{-1} y^{-1} in Madhya Pradesh and 4.15 - 4.66 t C ha^{-1} y^{-1} in Chhattisgarh. The highest sequestration of CO$_2$ was recorded in the month of August at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and September at Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh). It has been estimated that, the net ecosystem exchange (NEE) were high during the late monsoon period. In the month of April to May carbon is released into the atmosphere and forest act as source of carbon. This may be due to lower gross primary productivity (GPP) than the respiration (R$_{eco}$). The low GPP was recorded in this period due to low LAI. Data so far recorded, shows a seasonal variation in GPP, NEE and R$_{eco}$. The average NEE was higher in the wet season (May-September) than the dry season. This variation may be due to the monthly variation in meteorological condition. Determination of potentiality of carbon sequestration in mixed deciduous forests are very crucial. The findings of the present study may help the forest managers in forest carbon assessments and devising suitable strategies for sustainable management of the forests.

Fluxes measured by the eddy covariance systems provide a robust data which can be used for the calibration (such as maximum light use efficiency, optimum temperature, and VPD) and validation of the various ecosystem and carbon models, including the empirical, semi-empirical and process-based models for the estimation and prediction of the carbon fluxes at larger geographical scales. Long term measurements of carbon fluxes provide intense and detailed understanding of the carbon cycle processes. Continuation of ongoing measurements could help in predicting net carbon uptake at Northern Mixed Deciduous Forest, Khatpura (Madhya Pradesh) and Southern Mixed Deciduous Forest, Sonhat (Chhattisgarh) in near future.



References

Ahongshangbam, J, Patel, N. R., Kushwaha, S.P.S., Watham, T. and Dadhwal, V. K. (2016). Estimating gross primary production of a forest plantation area using eddy covariance data and satellite imagery. *Journal of the Indian Society of Remote Sensing,* 44(6), pp.895-904.

Amundson, R., Stern, L, Raisden. T. and Wang, Y. (1998). The isotopic composition of soil and soil respired CO_2. *Geoderma,* 82: 83–114.

Artigas, F., Shin, J. Y., Hobble, C., Marti-Donati, A., Schafer, K.V. and Pechmann, I. (2015). Long term carbon storage potential and CO_2 sink strength of a restored salt marsh in New Jersey. *Agric. For. Meteorol*., 200:313–321.

Baldocchi, D. D., Hincks, B. B. and Meyers, T. P. (1988). Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology*, 69(5):1331-1340.

Bhattacharya, S. K., Borole, D. V., Francy, R. J., Allison, C. E., Steele, L. P., Krummel, P., Langenfelds, R., Masarie, K. A., Tiwari, Y. K. and Patra, P. K. (2009). Trace gases and CO_2 isotope records from Cabo de Rama, India. *Current Science:* 1336-1344.

Boisvenue, C. and Running, S. W. (2006). Impacts of climate change on natural forest productivity–evidence since the middle of the 20th century. *Global Change Biology*, 12(5): 862-882.

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science*, 320(5882):1444-1449.

Burba, G. and Anderson, D (2010). A brief practical guide to eddy covariance flux measurements: principles and workflow examples for scientific and industrial applications. Li-Cor Biosciences.

Burba, G. (2013). Eddy covariance method for scientific, industrial, agricultural and regulatory applications: A field book on measuring ecosystem gas exchange and areal emission rates. LI-Cor Biosciences.

Campioli, M., Malhi, Y., Vicca, S., Luyssaert S., Papale, D., Peñuelas, J., Reichstein, M., Migliavacca M., Arain, M. A. and Janssens, I. A. (2016). Evaluating the convergence between eddy-covariance and biometric methods for assessing carbon budgets of forests. *Nat. Commun*., 7, 13717.

Canadell, J. G., Mooney, H. A., Baldocchi, D. D., Berry, J. A., Ehleringer, B., Field, C. B., Gower, S. T., Hollinger, D. Y., Hunt, J. E., Jackson, R. B., Running, S. W., Shaver, G. R., Steffen, W., Trumbore, S. E., Valentini, R. and Bond, B. Y. (2000). Carbon metabolism of the terrestrial biosphere: a multi-technique approach for improved understanding. *Ecosystems*, 3:115–130.

Chatterjee, D., Nayak, A.K., Swain, C.K., Tripathi, R., Chatterjee, S., Pradhan, A., Swain, P. and Mohanty, S. (2021). Eddy Covariance Technique for Measurement of Mass and Energy Exchange in Lowland Rice. NRRI Research Bulletin No.29. ICAR-National Rice Research Institute, Cuttack, Odisha, 753006, India. pp 34 + vi.

Chen, X., Zhang, X., Zhang, Y., Booth, T. and He, X. (2009). Changes of carbon stocks in bamboo stands in China during 100 years. *Forest Ecology and Management*, 258(7):1489- 1496.

Clark, D. A., Brown, S., Kicklighter, D. W., Chambers, J. Q., Thomlinson, J. R. and Ni, J. (2001). Measuring net primary production in forests: Concepts and field methods. *Ecol. Appl.,* 11: 356–370

Domke, G, Williams, C., Birdsey, R., Coulston, J., Finzi, A., Gough, C., Haight, B., Hicke, J., Janowiak, M. and De Jong, B. (2018). Forests Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report ed N Cavallaro,G Shrestha, R Birdsey, M A Mayes, R G Najjar, S C Reed,P Romero-Lankao and Z Zhu (Washington, DC: US Global Change Research Program), pp 365-398.

Du, Y., Pei, W., Zhou, H., Li. J., Wang, Y. and Chen, K. (2022). Net ecosystem exchange of carbon dioxide fluxes and its driving mechanism in the forests of the Tibetan Plateau. *Biochemical Systematics and Ecology*, 103, 104451.

Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Burba, G., Clement, R., Davis, K. J., Elbers, J.A., Goldstein, A.H., Grelle, A., Granier, A., Gu, J., Hollinger, D., Kowalski, A.S., Katul, G., Law, B.E., Malhi, Y., Meyers, T., Monson, R.K., Munger, J.W., Oechel, W., Tha, K., Paw, U., Pilegaard, K, Rannik, U., Rebmann, C., Suyker, A., Valentini, R., Wilson, K., Wofsy, S. (2002). Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. *Agric For Meteorol,* 113:53–74.

FAO (2020). Global Forest Resources Assessment 2020: Main report. Rome.

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., Ellis, P. W., Falcucci, A., Fourqurean, J. W. and Gopalakrishna, T. (2018). Natural climate solutions for the United States. *Sci. Adv*. 4 eaat1869.

Fei, X., Song, Q., Zhang, Y., Liu, Y., Sha, L., Yu. G., Zhang, L., Duan, C., Deng. Y., Wu, C., Lu, Z., Luo, K., Chen, A., Xu, K., Liu, W., Huang, H., Jin, Y., Zhou, R., Li, J., Lin, Y., Zhou, L., Fu, Y., Bai, X., Tang, X., Gao, J., Zhou, W. and Grace, J. (2018). Carbon exchanges and their responses to temperature and precipitation in forest ecosystems in Yunnan, Southwest China. *Sci Total Environ,* 616–617:824–840.

Foken, T. (2008). The energy balance closure problem: An overview. *Ecol. Appl.,* 18: 1351–1367.

FSI (2019). India State of Forest Report 2019. Forest Survey of India Dehradun.

FSI (2023). Forest Fire Activities. Forest Survey of India. https://www.fsi.nic.in/forest-fire-activities. (accessed in April, 2023).

Fu, Y. S., Campioli, M., Vitasse, Y., De Boeck, H.J., Van den Berge, J., AbdElgawad, H., Asard, H., Piao, S., Deckmyn, G. and Janssens, I. A. (2014). Variation in leaf flushing date influences autumnal senescence and next year's flushing date in two temperate tree species. *Proc. Nat. Acad. Sci.,* 111(20):7355–7360.

Grachev, A. A., Fairall, C. W., Blomquist, B. W., Fernando, H. J., Leo, L. S., Otarola-Bustos, S. F., Wilczak, J. M. and McCafrey, K. L. (2020). On the surface energy balance closure at different temporal scales. *Agric For Meteorol*., 281:107823.

Gray, A.N. and Whittier, T. R. (2014). Carbon stocks and changes on Pacific Northwest national forests and the role of disturbance, management, and growth. *Forest Ecology and management*, 328: 167-178.

Gu, L., Fuentes, J. D., Shugart, H.H., Staebler, R.M. and Black, T.A. (1999). Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: forests. *J Geophys. Res*., 104: 31421–31434.

Gudasz, C., Karlsson, J. and Bastviken, D. (2021). When does temperature matter for ecosystem respiration?. *Environmental Research Communications*, *3*(12), p.121001.

Huc, R., Ferhi, A. and Guehl, J. M. (1994). Pioneer and late stage tropical rainforest tree species (French Guyana) growing under common conditions differ in leaf gas exchange regulation, carbon isotope discrimination and water potential. *Oecologia:* 99:297-305.

Hutyra, L. R., J. W. Munger, S. R. Saleska, E. Gottlieb, B. C. Daube, A. L. Dunn, D. F. Amaral, P. B. de Camargo, and S. C. Wofsy (2007). Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. *J. Geophys. Res*., 112, G03008, doi:10.1029/2006JG000365.

ICFRE (2020 a). Ecosystem Services Improvement Project: Baseline Report of Forest Carbon Stocks of Project Areas of Madhya Pradesh. Indian Council of Forestry Research and Education, Dehradun.

ICFRE (2020 b). Ecosystem Services Improvement Project: Baseline Report of Forest Carbon Stocks of Project Areas of Chhattisgarh. Indian Council of Forestry Research and Education, Dehradun.

ICFRE (2020 c). Resource Manual: Measurement of Forest Carbon Stocks for Capacity Building of State Forest Departments. Indian Council of Forestry Research and Education, Dehradun (INDIA).

IPCC (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Pean, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B. (eds.) Cambridge University Press.

Ishida, A, Toma, T. and Marjenah (1999). Limitation of leaf carbon gain by stomatal and photochemical processes in the top canopy of *Macaranga conifera*: a tropical pioneer tree. *Tree Physiol.*, 19: 467–473.

Jia, J. T., Xue, Y., Jun-Fu Zhao, J. F., Yang, Z. Y., Shao-Feng Su, S. F., Wang, X. Y., Zhi-Pan Lin, Z. P., Guan-Ze, Wang, G. Z., Yang, L. Y. and Zhang, X. (2023). Atmospheric Exchange of Carbon Dioxide and Water Vapor above a Tropical Sandy Coastal Plain. *Water*, 15, 877.

Jiang K, Fu, B., Luo, L, Xiong, R., Men, Y., Li, B., Shen, G. and Tao, S. (2022). Attributed radiative forcing of air pollutants from biomass and fossil burning emissions. *Environ. Pollut*. 306, 119378.

Jiao, X., Yu, X., Ding, J., Du, Q., Zhang, J., Song, X., Bai, P. and Li, J. (2022). Effects of rising VPD on the nutrient uptake, water status and photosynthetic system of tomato plants at different nitrogen applications under low temperature. *Scientia Horticulturae*, *304*, 111335.

Kaimal, J. C., Izumi, Y., Wyngaard, J. C. and Cote, R. (1972). Spectral characteristics of surface-layer turbulence, *Q. J. R. Meteorol. Soc.*, 98(417): 563 – 589.

Keenan, T. F. and Williams, C. A. (2018). The terrestrial carbon sink. *Annu. Rev. Environ. Resour*., 43: 219-243.

King, A. W., Dilling, L., Zimmerman, G. P., Fairman, D. M., Houghton, R. A., Marland, G., Rose, A. Z. and Wilbanks, T. J. (2007). U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Executive Summary, The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle National Oceanic and Atmospheric Administration, National Climatic Data Centre.

Kirschbaum, M.U.F., Eamus, D., Gifford, R.M., Roxburgh, S.H. and Sands, P.J. (2001). Definitions of some ecological terms commonly used in carbon accounting. *Cooperative Research Centre for Carbon Accounting, Canberra*, pp.2-5.

Kuppers, M., Wheeler, A. M., Kuppers, B. I. L., Kirschbaum, M. U. F. and Farquhar, G. D. (1986). Carbon fixation in eucalypts in the field; analysis of diurnal variations in photosynthetic capacity. *Oecologia,* 70:273–282.

Law, B. E., Falge, E., Gu, L., Baldocchi, D. D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A. J., Falk, M., Fuentes, J. D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I. A., Jarvis, P., Jensen, N. O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw, U.H.K.T, Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S. (2002). Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. *Agric For Meteorol.,* 113:97–120.

Leuschner, C. (2002). Air humidity as an ecological factor for woodland herbs: leaf water status, nutrient uptake, leaf anatomy, and productivity of eight species grown at low or high vpd levels. *Flora-Morphology, Distribution, Functional Ecology of Plants*, *197*(4), 262-274.

Liu, L., Wang, X., Lajeunesse, M.J., Miao, G., Piao, S., Wan, S., Wu, Y., Wang, Z., Yang, S., Li, P., and Deng, M. (2016). A cross-biome synthesis of soil respiration and its determinants under simulated precipitation changes. *Glob. Chang. Biol*.: 22(4):1394–1405.

Loescher, H. W., Law, B. E., Mahrt. L., Hollinger, D. Y., Campbell, J. and Wofsy, S. C. (2006). Uncertainties in, and interpretation of, carbon flux estimates using the Eddy Covariance technique. *Journal of Geophysical Research*, 111, D21.

McGloin, R., Sigut, L., Havrankova, K., Dusek, J., Pavelka, M., Sedlak, P. (2018). Energy balance closure at a variety of ecosystems in Central Europe with contrasting topographies. *Agric. For. Meteorol.,* 248: 418–431.

McMillen, R. T. (1988). An eddy-correlation technique with extended applicability to non-simple terrain, *Boundary Layer Meteorol*., 43(3), 231 – 245.

Meir, P., Wood, T.E., Galbraith, D.R., Brando, P.M., Da Costa, A. C., Rowland, L. and Ferreira, L.V. (2015). Threshold responses to soil moisture deficit by trees and soil in tropical rain forests: insights from field experiments. *Bio. Sci,* 65(9):882–892.

Messori, G., Ruiz-Pérez, G., Manzoni, S. and Vico, G. (2019). Climate drivers of the terrestrial carbon cycle variability in Europe. *Environmental Research Letters*, *14*(6), p.063001.

Migliavacca, M., Reichstein, M., Richardson, A. D., Mahecha, M. D., Cremonese, E., Delpierre, N., Galvagno, M., Law, B., E., Wohlfahrt, G., Andrew Black, T. and Carvalhais, N. (2015). Influence of physiological phenology on the seasonal pattern of ecosystem respiration in deciduous forests. *Glob. Chang. Biol*.: 21(1):363–376.

Moncrieff, J. B., Clement, R., Finnigan, J. and Meyers, T. (2004). Averaging, detrending, and filtering of eddy covariance time series. *In: Handbook of Micrometeorology*, Springer, Dordrecht, pp.: 7–31.

Moncrieff, J. B., Massheder, J. M., De Bruin H, Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Søgaard, H. and Verhoef, A. (1997). A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *J. Hydrol.,* 188:589–611.

Nandy, S., Srinet, R. and Padalia, H. (2021). Mapping forest height and aboveground biomass by integrating ICESat-2, Sentinel-1 and Sentinel-2 data using Random Forest algorithm in northwest Himalayan foothills of India. *Geophysical Research Letters,* 48(14), p.e. 2021GL093799.

Niu, Z., Wang, L., Niu, Y., Hu, B., Zhang, M., and Qin, W. (2018). Spatiotemporal variations of photosynthetically active radiation and influencing factors in China from 1961 to2016. *Theoretical and Applied Climatology,* 137: 2049-2067.

Pathre, U., Sinha, A.K., Shirke, P.A. and Sane, P.V. (1998). Factors determining the midday depression of photosynthesis in trees under monsoon climate. *Trees,* 12:472–481.

Rawson, H. M., Begg J. E., and Woodward R. G. (1977). The effect of atmospheric humidity on photosynthesis, transpiration and water use efficiency of leaves of several plant species. *Planta,* 134, 5–10.

Reichstein, M. and Beer, C. (2008). Soil respiration across scales: The importance of a model–data integration framework for data interpretation. *J. Plant. Nutr. Soil. Sci.,* 171(3):344–354.

Ritchie, H., Roser, M. and Rosado, P. (2020). CO_2 and greenhouse gas emissions. Our world in data.

Running, S. W., Baldocchi, D. D., Turner, D. P., Gower, S. T., Bakwin, P. S., Hibbard, K. A. (1999). A global terrestrial monitoring network integrating tower fluxes, flask sampling, ecosystem modelling and EOS satellite data. *Remote Sen. Environ.,* 70:108–127.

Running, S. W., Nemani, R. R., Heinsch, F., A., Zhao, M., Reeves, M. and Hashimoto, H. (2004). A continuous satellite-derived measure of global terrestrial primary production. *Bioscience*, 54(6): 547-560.

Sarma, D., Baruah, K. K., Chakraborty, S., Karipot, A. and Baruah, R. (2019). Impact of ecosystem respiration on carbon balance in a semi-evergreen forest of Northeast India. *Curr. Sci.*, 116:751–757.

Singh, N., Parida, B. R, Chakraborty, J. S. and Patel, N. R. (2019). Net ecosystem exchange of CO_2 in deciduous pine forest of lower western Himalaya, India. *Res*., 8(2):98.

Srinet, R., Nandy, S., Watham, T., Padalia, H., Patel, N. R. and Chauhan, P. (2022). Measuring evapotranspiration by eddy covariance method and understanding its biophysical controls in moist deciduous forest of northwest Himalayan foothills of India. *Tropical Ecology,* 1-11.

Stocker, T. F., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Sulman, B.N., Roman, D.T., Yi, K., Wang, L., Phillips, R.P. and Novick, K.A. (2016). High atmospheric demand for water can limit forest carbon uptake and transpiration as severely as dry soil. *Geophysical Research Letters*, *43*(18), 9686-9695.

Sun, J., Peng, C., McCaughey, H., Zhou, X., Thomas, V., Berninger, F., Onge, B.S., and Hua, D. (2008). Stimulating carbon exchange of Canadian boreal forests II. Comparing the carbon budgets of a boreal mixed-wood stand to black spruce forest stand. *Ecological Modeling*, 219: 276-286.

Tenhunen, J. D., Lange, O. L., Gebel, J., Beyschlag, W. and Weber, J. A. (1984). Changes in photosynthetic capacity, carboxylation efficiency, and CO_2 compensation point associated with midday stomatal closure and midday depression of net CO_2 exchange of leaves of *Quercus suber*. *Planta*, 162:193–203.

Tiwari, Y. K., Revadekar, J. V. and Kumar, K. R. (2013). Variations in atmospheric Carbon Dioxide and its association with rainfall and vegetation over India. *Atmospheric Environment*, 68: 45-51.

Verlinden, M. S., Broeckx, L. S., Zona, D., Berhongaray, G., Groote, T. D., Serrano, M. C., Janssens, I. A. and Ceulemans, R. (2013). Net ecosystem production and carbon balance of an SRC poplar planation during its first rotation. *Biomass and Bioenergy,* 56: 412-422.

Vickers, D. and Mahrt, L. (1997). Quality control and flux sampling problems for tower and aircraft data. *J. Atmos Ocean Technol.,*14:512–526.

Wang, H. M., Saigusa, N., Zu, Y. G., Wang, W. J., Yamamoto, S. and Kondo, H. (2008). Carbon fluxes and their response to environmental variables in a Dahurian larch forest ecosystem in northeast China. *J. For. Res.* 19(1):1–10.

Waring, R. H. and Running, S. W. (2007). Forest ecosystem analysis at multiple time and space scales. *Forest Ecosystems*, 1-16.

Watham, T., Srinet, R., Nandy, S., Padalia, H., Sanjiv, K., Sinha, S. K., Patel, N. R. and Chauhan, P. (2020). Environmental control on carbon exchange of natural and planted forests in Western Himalayan foothills of India. *Biogeochemistry*, https://doi.org/10.1007/s10533-020-00727-x.

Watham, T., Padalia, H., Srinet, R., Nandy, S., Verma, P. A. and Chauhan, P. (2021). Seasonal dynamics and impact factors of atmospheric CO_2 concentration over subtropical forest canopies: observation from eddy covariance tower and OCO-2 satellite in Northwest Himalaya, India. *Environmental Monitoring and Assessment*, 193(2): 1- 15.

Watham, T., Patel, N.R., Kushwaha, S.P.S., Dadhwal, V.K. and Kumar, A.S. (2017). Evaluation of remote-sensing-based models of gross primary productivity over Indian sal forest using flux tower and MODIS satellite data. *International Journal of Remote Sensing,* 38(18): 5069-5090.

Webb, E. K., Pearman, G. I. and Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. *Q. J. R. Meteorol. Soc*., 106(447):85–100.

Xiao, J. and Moody, A. (2005). A comparison of methods for estimating fractional green vegetation cover within a desert-to-upland transition zone in central New Mexico, USA. *Remote Sensing of Environment,* 98(2-3): 237-250.

REFERENCES

Xiao, J., Zhuang, Q., Law, B. E., Baldocchi, D. D., Chen, J., Richardson, A. D., Melillo, J. M, Davis, K. J., Hollinger, D. Y., Wharton, S. and Oren, R. (2011). Assessing net ecosystem carbon exchange of US terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. *Agricultural and Forest Meteorology*, 151(1): 60-69.

Yu, Z., You, W., Agathokleous, E., Zhou, G. and Liu, S. (2021). Forest management required for consistent carbon sink in China's forest plantations. *For. Ecosyst.,* 8(1): 1-9.

Yuan, W., Zheng, Y., Piao, S., Ciais, P., Lombardozzi, D., Wang, Y., Ryu, Y., Chen, G., Dong, W., Hu, Z. and Jain, A.K. (2019). Increased atmospheric vapor pressure deficit reduces global vegetation growth. *Science advances*, *5*(8), p.eaax1396.

Zhang, L., Yu, G., Sun, X., Wen, X., Ren, C., Song, X., Liu, Y., Guan, D, Yan J, Zhang Y (2006). Seasonal variation of carbon exchange of typical forest ecosystems along the eastern forest transect in China. Sci China Ser D: *Earth Sci*., 49(2): 47–62.

Zhou, X., Gao, T, Takle, E. S., Zhen, X., Suyker, A. E., Awada, T., Okalebo, J., and Zhu, J. (2022). Air temperature equation derived from sonic temperature and water vapor mixing ratio for turbulent airflow sampled through closed-path eddy-covariance flux systems. Atmos. Meas. Tech., 15, 95–115.

Zotz, G., Harris, G., Koninger, M. and Winter, K. (1995). High rates of photosynthesis in the tropical tree, *Ficus insipida* Willd. *Flora* 190: 265–272.

Annexure I

Exponential equations developed between Air temperature (T_{air}) and NEE

Location	Year	Month	Equation	R^2
Khatpura	2021	April	$Y=0.0171e^{0.1618x}$	0.31
		May	$Y=0.1079e^{0.1214x}$	0.25
		June	$Y=0.0804e^{0.1394x}$	0.22
		July	$Y=0.0264e^{0.1823x}$	0.23
		August	$Y=9E\text{-}05e^{0.4383x}$	0.28
		September	$Y=5E\text{-}17e^{1.6196x}$	0.60
		October	$Y=0.0115e^{0.1745x}$	0.38
		November	$Y=0.1009e^{0.1372x}$	0.21
		December	$Y=0.2137e^{0.1872x}$	0.27
	2022	January	$Y=0.2538e^{0.1656x}$	0.28
		February	$Y=0.1385e^{0.1796x}$	0.33
		March	$Y=0.252e^{0.0886x}$	0.23
		April	$Y=0.168e^{0.1625x}$	0.47
		May	$Y=0.0037e^{0.2082x}$	0.31
		June	$Y=0.0514e^{0.146x}$	0.33
		July	$Y=0.0003e^{0.3693x}$	0.29
		August	$Y=2E\text{-}10e^{0.8435x}$	0.57
		September	$Y=0.0009e^{0.3287x}$	0.22
		October	$Y=1036e^{0.224x}$	0.23
		November	$Y=0.2218e^{0.2067x}$	0.26
		December	$Y=0.3635e^{0.1704x}$	0.32
	2023	January	$Y=9E\text{-}16e^{0.1239x}$	0.34
		February	$Y=1E\text{-}14e^{0.1121x}$	0.30
		March	$Y=7E\text{-}26e^{0.1985x}$	0.46
Sonhat	2021	April	$Y=0.0088e^{0.2371x}$	0.67
		May	$Y=0.0009e^{0.3205x}$	0.61
		June	$Y=0.0003e^{0.3564x}$	0.58
		July	$Y=0.0003e^{0.3592x}$	0.45
		August	$Y=1E\text{-}05e^{0.5032x}$	0.49
		September	$Y=0.0002e^{0.4064x}$	0.38
		October	$Y=0.0002e^{0.428x}$	0.26
		November	$Y=0.1076e^{0.2267x}$	0.36
		December	$Y=0.301e^{0.2198x}$	0.37
	2022	January	$Y=0.2304e^{0.1796x}$	0.22
		February	$Y=1.5065e^{0.0678x}$	0.27
		March	$Y=0.2598e^{0.11x}$	0.43
		April	$Y=0.0969e^{0.13x}$	0.43
		May	$Y=0.0852e^{0.1264x}$	0.34
		June	$Y=0.0425e^{0.1572x}$	0.44
		July	$Y=0.0284e^{0.1828x}$	0.42
		August	$Y=0.0049e^{0.2634x}$	0.29

	September	$Y=0.0007e^{0.3364x}$	0.25
	October	$Y=8E\text{-}06\ e^{0.5363x}$	0.52
	November	$Y=0.0317e^{0.1341x}$	0.21
	December	$Y=0.1069e^{0.1762x}$	0.26
2023	January	$Y=2E\text{-}20e^{0.1636x}$	0.41
	February	$Y=1E+22e^{-0.17x}$	0.32
	March	$Y=5E\text{-}22e^{0.1723x}$	0.24

ISBN: 978-81-94-9306-8-6

Designed & Printed at Shiva Offset Press, Dehradun, Ph. 0135-2715748