Parametrization of the DO_3SE Model for two tree species

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Dissertation submitted for the partial fulfilment of BS-MS dual degree in Science

Indian Institute of Science Education and Research Mohali

April 2019

Certificate of Examination

This is to certify that the dissertation titled "Parametrization of the DO_3SE Model for two tree species" submitted by Ms. Deepali Sehgal(MS14093) for the partial fulfillment of BS-MS dual degree program of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. V. Sinha (Supervisor)	Dr. Baerbel Sinha	Dr. Anoop Ambili

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. V. Sinha at the Indian Institute of Science Education and Research Mohali. This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgment of collaborative research and discussions. This thesis is a bona fide record of original work done by me and all sources listed within have been detailed in the bibliography.

Deepali Sehgal

(Candidate)

Dated –

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. V. Sinha

(Superviosor)

Acknowledgment

I wish to express my gratitude to Dr. V. Sinha and Dr. Baerbel Sinha for their guidance.

I thank my lab members Aastha, Dr. Anita, Gaurav Sharma, Pallavi, Savita, Harshita, Haseeb, Ashish, Abhishek, Tess, Jatinder, Pooja, Abhishek Verma, Lejish, Priya, Savita, Abhilasha and Ritika.

I also thank my parents for their unconditional love and lastly, I extend a sincere thanks to Dr. V. Rajesh and all my friends for believing in me at all times.

Deepali Sehgal

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Notation (Abbreviations)

AOT40	Accumulated Ozone exposure over a Threshold of 40 ppb.
DO_3SE	Deposition of Ozone for stomatal exchange (model)
g_s	Stomatal conductance.
POD_Y	Phytotoxic ozone dose above a threshold of Y.
SWP	Soil water Potential
VPD	Vapor pressure deficit.
PAR	Photosynthetically active radiation.
NO_x	Nitrogen Oxides (NO and NO_2)
RH	Relative Humidity
CO_2	Carbon dioxide
O_3	Ozone
RH	Relative Humidity
CSV	Comma-separated values

Contents

Abstract

Sessile nature of trees and plants call for continuous adaptation to pandemic changes in environment and stomata plays a crucial role in allowing and blocking the intake of various gases and water vapor. Tropospheric O_3 is a phytotoxic pollutant and g_s values along with the environmental factors affect its uptake by the leaves of the trees. Dry deposition on vegetated and non-vegetated surfaces of the plant accounts for about 25% of the total Ozone removed from the troposphere. The response of Stomata to PAR, CO_2, VPD, and Temperature was studied and plotted for two trees i.e. *Populous Deltoides* and *Ficus Religiosa.* Also, seasonal variation in g_s values was obtained by taking g_s measurements in the field for both the trees using leaf porometer.

The study also aimed to investigate the applicability of DO_3SE Model to *Populous Deltoides* and *Ficus Religosa.* The model performance was assessed by comparing modeled vs measured g_s.

CHAPTER 1

INTRODUCTION

1.1 Stomatal Conductance

All living organism must adapt to the variation in environmental conditions to survive. Like, some birds migrate to escape the unfavorable environmental conditions (behavioral adaptation). However, the sessile nature of trees and plants call for continuous adaptation to the pandemic changes in environment and stomata plays a crucial role in that.

Stomata are oval-shaped opening which are distributed throughout the aerial epidermis of vascular plants and are either present on both sides of the leaf (amphistomatic) or only on one side of the leaf (hypostomatic).

The closing and opening of these pores lead to regulation of gases (mainly CO_2 and water vapor) in the plant.

- Therefore, they help in balancing out the process of transpiration and photosynthesis in the plant (Chaerle et al., 2005).
- They do not allow the leaves to reach high temperatures by adjusting the transpiration-driven water flow such that a cooling effect is delivered on the leaf surface [1].

Plants can change the frequency (expressed as Stomatal Density per unit area) at which stomata develop to adjust better to the existing environmental conditions. The distribution pattern of stomata helps the plant to adjust according to the CO_2 levels and water availability.

The pattern of stomatal distribution thus varies within species and generally, the number of stomata has been found to be the greatest on the abaxial (bottom) side of the leaf to prevent the loss of water as it is less exposed to heating [18].

There are two guard cells that surround the stomata. The increase or decrease of solutes in the guard cells (like potassium ion) governs the stomatal aperture. The turgor pressure of these cells can change quickly, permitting quick adaption to the fluctuating environmental conditions.

Stomatal Conductance is the measure of the rate of passage of CO_2 entering or water vapor exiting (transpiration) through stomatal and is usually expressed in mmol/m^2s.

g_s = f (size, density, and degree of opening of the stomata).

Thus wide open stomata indicate high g_s values, and subsequently representing a higher transpiration and photosynthetic rates.

1.2 Poplar and Peepal - Their Importance, Distribution, Phenology, and Emission OF VOCs

1.2.1 *Populus Deltoides*

Common Name: eastern cottonwood, Poplar

Family: Salicaceae

Native Range: Eastern and central United States

Flower: Insignificant

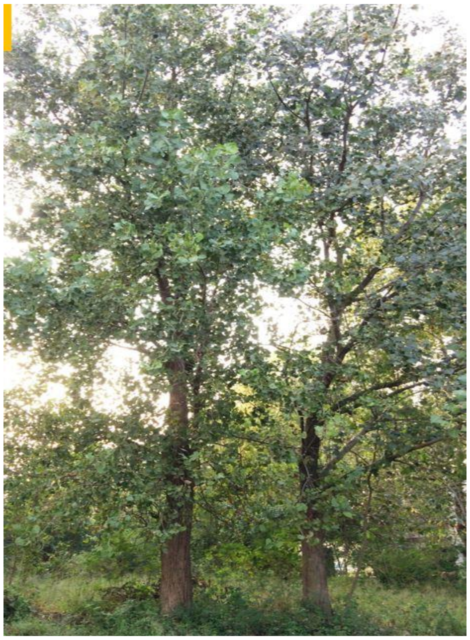
Genus: Populus

Distribution in India: Western U.P, Punjab, Haryana and outer plains/valleys in Uttaranchal and Himachal Pradesh.

Area: 60,000 ha equivalent

Planting Sites: Irrigated Agricultural Land

Susceptible to: Disease, fire, drought



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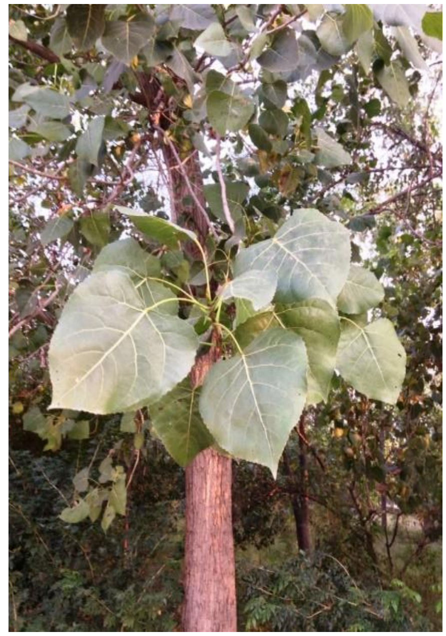


B

Photo 1A: *Populus Deltoides* trees located near CAF; 1B Branches of one of the Poplar tree. Photo Taken by Dr. Anita.

Poplar is a fast-growing deciduous species which was introduced in India in the 1950s to serve the match industry and continues to grow on a large scale in India. Most of the plantations are composed of *Populus deltoides* which is an exotic species [6].

USES (WOOD AND FIBRE) -

- Used in Match industry and as a source of firewood.
- Poplar is used in agroforestry in irrigated plains of Northern India, Punjab, U.P, H.P, A.P, and J&K [25]

ENVIRONMENTAL BENEFIT –

- Provides shade, beautify the landscape, and protect streambanks from soil erosion
- It endures summer heat and soot

- Farmstead windbreaks of poplars protect farm homes, buildings, animals, etc. from winds.
- Decreases noise and dust and provide wildlife habitat.
- acts as filters for contaminants such as excess nitrates and pesticides and prevent them to reach the stream (riparian buffer)
- Ideal for disposal of agricultural, industrial, and community wastewater as they can take up large quantities of water.
- Currently being used as an environmentally acceptable source of biomass for wood and energy (Cleaner and Cheaper approach)
- CO_2 contained in a grown tree remains stored in the logs (Carbon Sink).

However, its population in natural stands is gradually declining owing to deforestation and forest fires which can be seen as a problem of major concern given the innumerous purpose it serves.

Biology-

Phenology

Yellowing of leaves: November (last week) - December
Shedding of leaves: January
Growth of new leaves - March

Leaf biology

Leaves are broad yet narrow, 8 to 15 cm long, amphistomatic, deltoid (triangular) in shape with its edges being coarse and curved. Stem and petiole are flat, apex is pointed.

Photo 2: Scanned Leaf Image of *Populus Deltoides* illustrating its veins and structure, Reproduced by Dr. Anita.

BIOGENIC VOLATILE ORGANIC COMPOUNDS (VOC)

Plants produce VOCs as they help to combat the trees to deal with various biotic as well as abiotic stresses (heat, pollution). VOC’s emission increases plants defense against herbivores and bacterial/fungal pathogens [20].

If emitted in large enough amounts VOC's can cause detrimental impacts on the chemical reactions in the atmosphere [29]. For example, isoprene and monoterpene emissions by trees lead to O_3 production (reviewed by Fehsenfeld et al., 1992). The hazardous impacts of ozone in the lower atmosphere will be described in section 1.3.

Table 1: VOC emission for Poplar and Peepal

FAMILY	ISOPRENE (µg g(LDW)$^{-1}$ h^{-1}	MONOTERPENE(µg g(LDW)$^{-1}$ h^{-1})	Ref
P. Deltoide	**37.0**	**-**	**[7]**
F. religiosa Linn.	**76.5**	**-**	**[8]**

1.2.2 *F. religiosa Linn.*

Common Name: Peepal, Bodhi Tree

Family: Moraceae

Native Range: Indian Subcontinent and South-East Asian Countries

Genus: Ficus

Distribution in India: grown throughout India but mainly in Haryana, Bihar, Kerala, Madhya Pradesh and Ranthambore National Park.

Planting Site – vicinity of temples, along roads, streets and park

Photo 3: *Ficus religiosa L* tree located at the parking area of CAF, IISER MOHALI, and Picture taken by me

Ficus religiosa L. is the most widely known member of the genus *Ficus* and is popular by many common names. It is a medium-sized, fast-growing, long-living deciduous tree that is sacred to both Hindus and Buddhists. It is native to India but has been spread worldwide through cultivation. References to *F. religiosa* are found in several ancient religious texts.

BIOLOGY

Leaf Biology:

- Heart shaped leaves.
- Shiny, thin, and bear reticulate venation.
- leaf is hypostatic

Phenology - Shedding of Leaves: March and April

Photo 4: Scanned Leaf of Peepal Tree, Scanning done

By Dr. Anita.

1.3 TROPOSPHERIC OZONE

Ozone is an important trace gas of the troposphere (10-200ppbv).
The two main sources of O_3 in the troposphere are -

- Stratospheric Transport
- By oxidation of CO and hydrocarbons in the presence of NO_x (Chemical Production).

Besides being an important greenhouse gas, 'ground-level ozone' is a short-lived pollutant (The Royal Society, 2008) and also a source of OH radical which causes chemical oxidation in the troposphere [24].

1.3.1 HAZARDOUS IMPACTS OF GROUND-LEVEL OZONE POLLUTION

It was back in the 1950s that the harmful effects of O_3 on plants were first identified. It's now identified as a significant bucolic air pollutant having adverse effects on human health, vegetation, and materials [19].

Plants can withstand a certain concentration of O_3 by detoxification process but when it exceeds that level, the gas can cause severe effects on the population dynamics of forest trees, biochemistry, physiology, and community structure (Karnosky et al., 2005).

National Ambient Air Quality Standard, which sets O_3 primary and secondary levels in India, prescribes it to be 100 $\mu g/m^3$ (8hr) and 180 $\mu g/m^3$ (1hr) respectively i.e, approximately equal to 50 ppb (8hr) and 90 ppb (1hr) at NTP [9].

The effects mentioned below can be in response to cumulative or short-term episodes of O_3 exposure –

In Humans

- Breathing O_3 can cause many health problems like coughing, congestion and throat irritation, asthma.
- It can reduce the functional capacity of the lung and inflame its lining. Recurrent exposure might scar lung tissue permanently.

"Anthropogenic O_3 exposure caused 0.7 ± 0.3 million global deaths in the year 2000". [10]

O_3 Damage to Vegetation

- Visible leaf damage in the form of stipples around stomata and premature aging of leaves.
- Reduction in the above- and below-ground growth and biomass.
- Reduction in flower number, flower biomass, and seed production.
- Higher susceptibility to abiotic stresses such as drought e.g. through loss of control on stomata and biotic stresses e.g. pest attacks and diseases [28].

- Foliar Visible symptoms like necrosis, reddening and bronzing of leaf.
- Reduced net photosynthesis which in turn is related to a decline in growth and yield of crops [11]. (Research indicates that O_3 alone was responsible for 90% crop loss caused by air pollution [12].
- It can reduce the stomatal conductance affecting the reproductive growth of the plant.
- Alter stomatal response to environmental stimuli [26].

1.3.2 DRY DEPOSITION: LEAVES AS SINK OF TROPOSPHERIC O_3

- O_3 is predominantly eliminated from the troposphere by dry deposition and chemical destruction.
- In fact, dry deposition accounts for 25% of the total O_3 eliminated from the troposphere [27] and thus is highly land cover dependent.
- It has been observed that deposition to vegetated surfaces of a plant is generally faster than deposition to its non-vegetated surfaces.
- At vegetated surfaces, around 30–90 % of O_3 dry deposition takes place via the stomata as uptake (Fowler et al., 2001; Cieslik, 2004; Fowler et al., 2009).

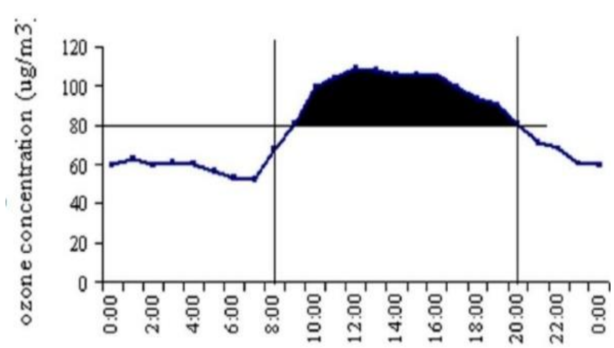
Plants and Trees show very less resistance to O_3 uptake and thus O_3 from lower atmosphere gets settled as dry deposition on vegetation. O_3 enters the plants through stomatal pores and on entering inside the plant reacts with the cell wall components to generate Reactive Oxygen Species (ROS). These reactions induce an active production of other ROS, including superoxide radicals, hydrogen peroxide, and hydroxyl radicals. Therefore only the O_3 molecules entering the leaves through the stomata will be harmful to the plants (Fuhrer, 2000). The quenching capacity of ROS in the apoplast through reactions with antioxidants marks the line of defense against O_3 damage. Plants, however, suffer indirect costs to counter the increase in ROS by the detoxification process. At high levels, ROS can cause programmed cell death. If ROS produced by O_3 inside leaf tissues are not scavenged by antioxidants then visible foliar injury can be seen (Ashmore, 2005). For example, a study conducted in Europe established that 80 semi-natural vegetation species and 30 crops growing in 16 countries showed symptoms of visible injury along with other negative effects such as reduction in biomass and yield in the period of 1994-2006 (Mills et al., 2011).

g_s is a key factor determining the amount of O_3 uptake by plants (Wieser and Havranek, 1993) and this underlines the need to study about the stomatal trends of different trees. For e.g. – The planting of C3 and C4 plant species that have high g_{night} in areas where phytotoxic O_3 levels have been recorded can contribute to a significant proportion of daily O_3 uptake (up to 9%). [13]

1.3.3 ESTABLISHMENT OF CRITICAL LEVELS FOR O_3

Critical levels are understood as the maximum concentration of an air pollutant above which, it can adversely affect the physiology of plants. In order to calculate critical levels, mapping manual is used (Mills, 2017). Critical levels of O_3 for trees, crops, and semi-natural vegetation can be calculated either by cumulative stomatal flux or the cumulative exposure. The two types of metrics for risk assessment are –

1. Concentration-based AOT 40 Exposure Index



AOT 40 - the exposure based critical level for O_3 was the most employed (LRTAP Convention 2011) and the accumulated dose over the threshold value of 40ppb was a vital indicator to protect the vegetation in Europe.

Figure 1: AOT40 Calculation Method; Reproduced from Banja et al, 2011, figure 2.

The AOT 40 is defined as the sum of the differences between hourly mean O_3 concentrations (in ppb) and a threshold value of 40 ppb (80 g/m^3) for each hour when the concentration exceeds 40 ppb, accumulated during daylight hours when global radiation exceed 50 W/m^2 [14].

$AOT40 = \int \max(O_3 - 40ppb, 0.0)\, dt$

2. STOMATAL FLUX BASED MODEL - DO_3SE

DO_3SE model was accepted by the EMEP LRTAP Convention in 2007. It is a dry deposition model designed to estimate the total and stomatal deposition of O_3. It models the stomatal flux of O_3 for an upper canopy sun-lit leaf using a multiplicative algorithm and is able to estimate O_3 dry deposition to both stomatal and non-stomatal components of vegetated surfaces [15].

NEED FOR DO_3SE MODEL

AOT 40 only considers ozone levels in the atmosphere above the leaf surface and hence is biologically less relevant for O_3 impact assessment. Moreover, it does not take into account how O_3 uptake is affected by factors like climate, soil and plant factors. Scientific evidence suggests that observed effects of O_3 on vegetation are more strongly related to the uptake of ozone through the stomata than to the concentration of O_3 in the surrounding atmosphere of the plant [23].

The DO_3Se considers the variation in stomatal opening and closing with the climatic, soil and plant factors. It was agreed at the Ispra workshop in 2009 to standardize the terminology for the accumulated stomatal flux over a specified time interval as POD_Y which is defined as phytotoxic O_3 dose above a threshold flux of Y during a specified time and is also denoted as the effective dose or effective flux". [16]

As stated before, plants have a defense mechanism to detoxify some of the absorbed O_3 and it is accounted by including concentration X in AOT_x (X being 40ppb) and an hourly cut-off Y flux in POD_y (Y=1nmol m^2 PLA s^{-1}).

The response of g_s to environmental variation has been described by a multiple algorithm first formulated by Jarvis (1976) –

$g_s = f(Q)\, f(D)\, f(T)\, f(\Psi)$ ------- - **(1)**

Where Q is PAR, D is VPD, T is Temperature, Ψ is leaf water potential – [8]

Jarvis's algorithm was later modified by Emberson et al. (Eq 2) and DO_3SE employs this new equation which incorporates the influence of air temperature, VPD, PAR, SWP, O_3 concentration, and plant phenology on maximum g_s and forms the core of the leaf O_3 flux model -

$$g_{sto} = g_{max} \times f_{phen} \times f_{light} \times max\{f_{\min}, \ (f_{temp} \times f_{VPD} \times f_{SM})\} \text{ ----- } (2)$$

In equation (2), parameters are defined as follows:

g_{sto} is the estimated stomatal diffusive conductance (mmol H_2O m^{-2} s^{-1}) and g_{max} is the species maximum stomatal conductance (mmol H_2O m^{-2} s^{-1}). f_{min} is the relative minimum stomatal conductance.

The parameters $f_{phen,}$ $f_{vpd,}$ $f_{light,}$ $f_{phen,}$ f_{SW} are all expressed in relative terms i.e they take up values between 0 and 1. These parameters modify the maximum stomal conductance in different ways. The protocol for plotting these functions along with the equations are described in section 2.4.

CHAPTER 2

MATERIALS AND METHODS

2.1 SITE DESCRIPTION

The Experimental site was located at the Indian Institute of Science Education and Research Mohali (30.6650° N and 76.7300° E) near an air monitoring station.

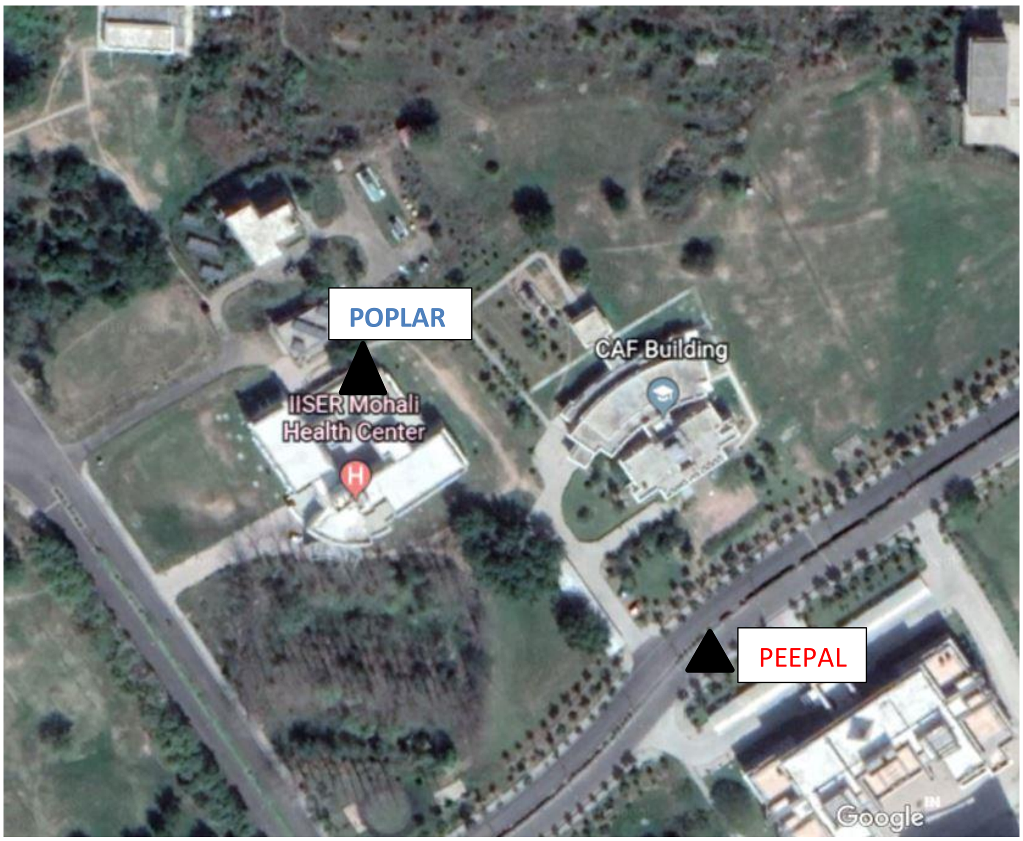


Figure 2: Shows the Experimental Site at IISER Mohali Campus where CAF buiding, IISER Mohali Health Centre, *Populous Deltoides* and *Ficus Religiosa L.* tree species are located. (Reproduced from Google Earth)

g_s measurements were taken from 3 Poplar and 2 Peepal trees. Table 2 illustrates the total number of measurements taken from both the tree species during 0-23 hour for two seasons i.e. Monsoon and Post-Monsoon.

Table 2 – Indicates the number of primary data measurements taken from Poplar and Peepal using leaf porometer.

HOUR OF THE DAY	MONSOON	POST - MONSOON	HOUR OF THE DAY	MONSOON	POST - MONSOON
0-1	55	38	12-13	52	124
1-2	48	48	13-14	70	108
2-3	40	21	14-15	93	117
3-4	60	50	15-16	74	111
4-5	45	27	16-17	65	127
5-6	37	19	17-18	82	76
6-7	34	13	18-19	85	57
7-8	30	9	19-20	77	79
8-9	63	55	20-21	76	65
9-10	43	89	21-22	63	77
10-11	61	113	22-23	46	25
11-12	56	154	23-24	51	28

Table 3 - Indicates the number of primary data measurements taken from Peepal

HOUR OF THE DAY	MONSOON	POST-MONSOON	HOUR OF THE DAY	MONSOON	POST-MONSOON
9-10	9	6	16-17	11	10
10-11	15	6	17-18	9	6
11-12	11	10	18-19	9	6
12-13	6	9	19-20	6	4
13-14	12	10	20-21	-	3
14-15	10	9	21-22	4	7
15-16	11	9	22-23	5	-

2.2 LEAF POROMETER

Photo 5: Leaf Porometer Controller (left) and Sensor Head (right), photo taken by me

A steady state (Decagon SC-1 device) leaf porometer was used to measure g_s values of Poplar and Peepal in the field from August-December. It can display readings in three units-

$mmol/m^2s$, m^2s/mol, s/m

WORKING PRINCIPLE – [17]

It measures the stomatal conductance of the leaf by putting the stomatal conductance of the leaf in series with two known conductance elements.

For leaves that are well ventilated and boundary layer conductance does not vary and is large, vapor flux along the diffusion path can be determined by using the RH difference between nodes 1 and 2 as follows-

$F_{vapor} = g_{s+d1}(C_{leaf} - C_1)$ ------- (1)

Where g_{d2} is the vapor conductance of the diffusion path between node 1 and node 2, C_1 is the mole fraction of vapor at node 1 and C_2 is the mole fraction of vapor at node 2.

VAPOR FLUX BETWEEN NODES 1 AND 2 can be written from eq (1) as –

$$F_{vapor} = g_{d2}(C_1 - C_2) \text{ ------------ (2)}$$

The C values are related to RH by Equation (3)

$$C_{i} = \frac{h_r e_s T_a}{P_{atm}} \text{------------------ (3)}$$

where h_r is RH, $e_{s*}(T_a)$ is saturated vapor pressure at the temperature (T_a) and P_{atm} is the atmospheric pressure.

g_{d2}, is defined by equation (4) is used:

$$g_{d2} = \frac{\rho D_{vapor}}{d_2} \quad \text{-------------- (4)}$$

where ρ is the density of the air and D_{vapor} is the diffusivity of the water vapor.

Placing C and g values from eq (3) and (4) in eq (2).

$$F_{vapor} = \left[\frac{\rho D_{vapor}}{d2}\right] \frac{1}{Patm} [hr_1 e_s(T_{a1}) - hr_2 e_s(Ta_2)] \text{--------------- (5)}$$

ASSUMPTION 1

RH within the leaf tissue is 1

Using assumption 1, $C_{leaf} = \frac{e_s(T_a)}{P_{atm}}$ ------ (6)

VAPOR FLUX BETWEEN NODE 1 AND THE LEAF

$$F_{vapour} = g_{s+d1}(C_{leaf} - C_1) \text{ ----------- (7)}$$

ASSUMPTION 2

Temperature of the leaf is equal to the temperature of the first humidity sensor

$$F_{vapour} = g_{s+d1} \left(\frac{1}{P_{atm}}\right) [e_s(T_{a1})(1 - h_{r1}) \text{ -------------- (8)}$$

ASSUMPTION 3

All conductances are in series so that flux is constant between any two nodes

Therefore, Eq (2) and (3) can be equated to solve for g_{s+d1}

And

$g_{d1} = \rho D \frac{vapour}{d_1}$ ------------ (9)

Since all conductance are in series –

$$\frac{1}{g_s} = \frac{1}{g_{s+d_1}} - \frac{1}{g_{d1}} \text{ -------- (10)}$$

Putting values of g_{d1} and g_{s+d1} in eq 10 will yield -

$$g_s = \frac{\rho D_{vapor}[hr_1 e_s(Ta_1) - hr_2 e_s(Ta_2)]}{[e_s(Ta_1)(1-hr_1)]d_2 - [hr_1 e_s(Ta_1) - hr_2 e_s(Ta_2)]d_1} \text{ ------ (11)}$$

For the decagon leaf porometer, the two distances are –

d_1= 3.35 mm and d_2 = 11.43 mm

"Therefore, g_s is a function of the distances between humidity sensors, temperature, and the two RH readings".

Eq 11 is employed by the instrument to display the g_s value on the screen.

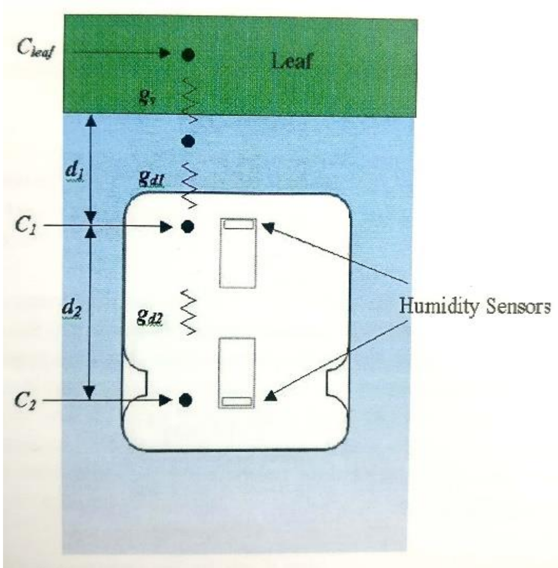


Figure 3: Image to explain the working principle of leaf porometer. Reproduced from Leaf Porometer Manual.

SOURCES OF ERROR AND HOW TO AVOID THEM

1. INSTRUMENTAL ERROR – Instrument displays measurements within an accuracy of 10%. So two consecutive reading should be within 50 mmol m^2 s^{-1} range of each other. If, not, then a further reading must be taken.
2. AVOID CHOOSING LEAVES THAT ARE IN SHADE – Stomata is sensitive to light (described in section 3.1) and hence taking measurements from leaves that are in shade or not fully exposed to the sun must be avoided. Leaves that are exposed to sun must be selected.
3. LESS PHYSICAL CONTACT WITH THE LEAF - Besides, the instrumental errors, error in measurements can further be augmented by our breathing. As we breathe, we exhale CO_2 and an increase in CO_2 concentration causes stomata to close (in section 3.1). Hence, a slight deviation in measurement values can be expected while taking measurements, however, this effect will be of particular consideration while taking measurements in the closed chambers. Thus measurements should be taken while maintaining optimum proximity from the leaf.
4. SELECTION OF LEAF – Leaves that have fully emerged, green, clean, dry, sun-lit, disease and damage-free should be chosen for measurement.

SCOPE OF INSTRUMENT -

In my opinion, the instrument has a scope for improvement in terms of its night usage. At night it's difficult to use the instrument alone, as the display screen has low brightness. This level of brightness works fairly well during the daylight hours however at night a companion is needed to shine the torch at the display screen or you yourself can use mobile phones light to see the screen. The instrument can be designed such that there is a brightness adjustment option just like our phones or a LED lighting screen can be installed.

2.3 INPUTS IN DO$_3$SE MODEL

2.3.1 The "Input data format" page –

Hourly averaged values of the following parameters mentioned in Table 4 were uploaded in the CSV format for the year 2018. CSV format is the most portable to work with and thus the model only accepts excel file in this format and the output file are generated in CSV format too.

INPUTS	UNITS	INSTRUMENT
Pressure	kPa	Decagon Device
Soil Moisture	V/V	Decagon Device
Humidity	RH	Decagon Device
PAR	$\mu mol/m^2s$	Decagon Device
Global radiation	Wh/m^2	AQS
Measured Ozone density	ppb	Thermo Fischer Model 49i
Temperature	Celsius	Decagon device
VPD	kPa	Calculated from Temp and humidty
Wind Speed	m/s	AQS
Precipitation	mm	AQS

Table 4: Inputs required for DO3SE Model stating the instruments from which they were taken.

2.3.2 The "Location properties" page

This page asks for parameters relating to the location of the experimental site.

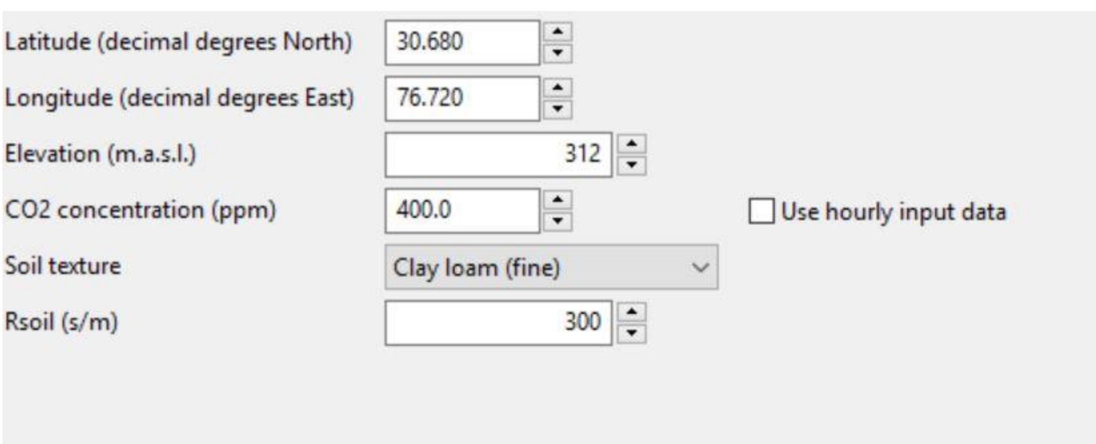


Photo 6: Screenshot of the entries for "location page" used for both the trees taken by me.

2.3.2 The "Measurement data" page

Ozone concentration and wind speed data was taken from the Ambient Air Quality Station located (AAQS) located at an approximate height of 20m above ground. Soil water measurement depth allows the model to calculate soil water data for a particular depth.

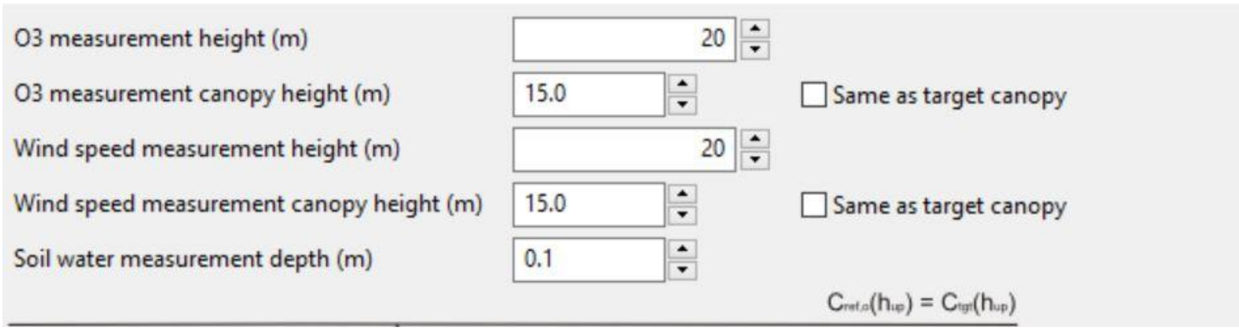


Photo 7: Screenshot of the "measurement data page" that includes the height at which O_3 and wind speed was measured (i.e. the height of Meteorological station).

2.3.4 The "Environmental response" page

This page contains parameters for response functions like $light_a$, T (min), T(max), T(opt), VPD(min), VPD(max) which were calculated for each tree. (See section 3.2)

2.4 PLOTTING RESPONSE FUNCTIONS

PROTOCOL –

1. g_s measurements were downloaded from the leaf porometer instrument on the desktop using the leaf porometer utility software.
2. For the corresponding date-time of each g_s measurement, meteorological parameters like temperature, soil moisture, humidity, PAR were attained (g_s and meteorological parameters were merged date-wise using MS-Excel's Microsoft Query function).
3. Then, g_{max} was determined for both tree species.
4. Each g_s measurement was divided by the g_{max} to get relative g values.

5. Relative g vs PAR/VPD/Temperature/SWP graphs were plotted to give scattered points.
6. In order to get the functional dependency between g_s and meteorological parameters boundary line approach was used. The equations used from Mapping Manual [23] are listed below –

I F_{light}

$$f_{light} = 1 - EXP((-light_a) * PPFD)$$

Where PPFD represents PAR in units of μmol/m^{2}s.

II F_{temp}

$$f_{temp} = \max\left\{f_{min}, \left[\frac{T - T_{min}}{T_{opt} - T_{min}}\right] * \left[\frac{T_{max} - T}{T_{max} - T_{opt}}\right]^{bt}\right\}$$

$$bt = \frac{T_{max} - T_{opt}}{T_{opt} - T_{min}}$$

Where f_{min} is the relative minimum g_s that occurs during daylight hours.

III F_{vpd}

$$VPD = e_s(T_a)(1 - h_r)$$

$$e_s(T_a) = a * \left\{\frac{\exp(b * T_a)}{T_a + c}\right\}$$

$$f_{VPD} = \min[1, \max\left\{f_{min}, \left((1 - f_{min}) * \frac{VPD_{min} - VPD}{VPD_{min} - VPD_{max}}\right) + f_{min}\right\}]$$

IV F_{SW}

$$f_{SW} = \min\{1, max\left\{f_{min}, \left((1 - f_{min}) * \frac{SWP_{min} - SWP}{SWP_{min} - SWP_{max}}\right) + f_{min}\right\}\}$$

CHAPTER 3

RESULTS

3.1 RESPONSE OF STOMATA TO THE ENVIRONMENT

As mentioned earlier, stomata are important for increasing plant's performance, agricultural productivity, to maintain global CO_2 and hydrological cycles. It also plays a key role in helping the plant to adapt to changing environmental conditions and to stress by adjusting its stomatal aperture. Thus it is of vital importance that we try to expand our understanding of the way stomata respond to different environmental parameters.

1. **Carbon Dioxide (CO_2)**

For most of the vegetation a decrease in g_s has been observed under elevated CO_2 concentrations. However, an increase in g_s can occur under high CO_2 concentration in hot and dry environments (high VPD). [2]

As atmospheric CO_2 concentration is expected to increase over the decades, a reduction in Stomatal Density is the expected trend in both geological times and under laboratory conditions (Woodward, 1987). When atmospheric CO_2 concentration will be high, there will be an increased probability of the gas to enter inside plants which means that the plant can reach an optimum cell CO_2 density with fewer stomata. However, there are few reports that suggest higher Stomatal Density values for some vegetation that grows in areas of high CO_2 than those grown at lower CO_2 concentrations [3].

Potential environmental impacts-

In 2011 Lammertsma et al. conducted research in Florida and concluded that trees and plants will continue to cope up with rising levels of CO_2, by closing stomata and reducing transpiration. This will have serious consequences on the hydrological cycle and climate. Lesser transpiration rates can alter rainfall patterns. Moreover, transpiration leads to surface cooling and therefore, lower transpirations rates will cause a stronger surface temperature increase than currently anticipated (Gedney et al. 2006). Increasing atmospheric CO_2 will decrease the dry deposition rate of air pollutants as it decreases g_s.

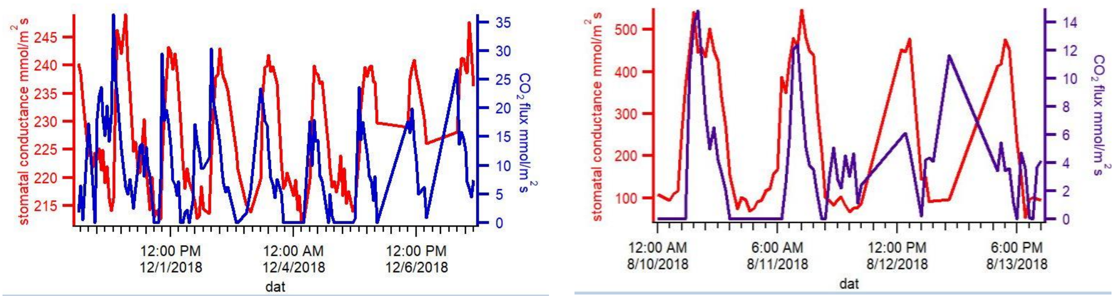


Figure 4: Plot of g_s and CO_2 assimilation for poplar monsoon and post-monsoon season

Figure 4 illustrates that the amount of CO_2 entering the trees via stomata will be maximum when g_s is maximum. Thus, the peaks of stomatal conductance and CO_2 flux coincide.

2. HUMIDITY

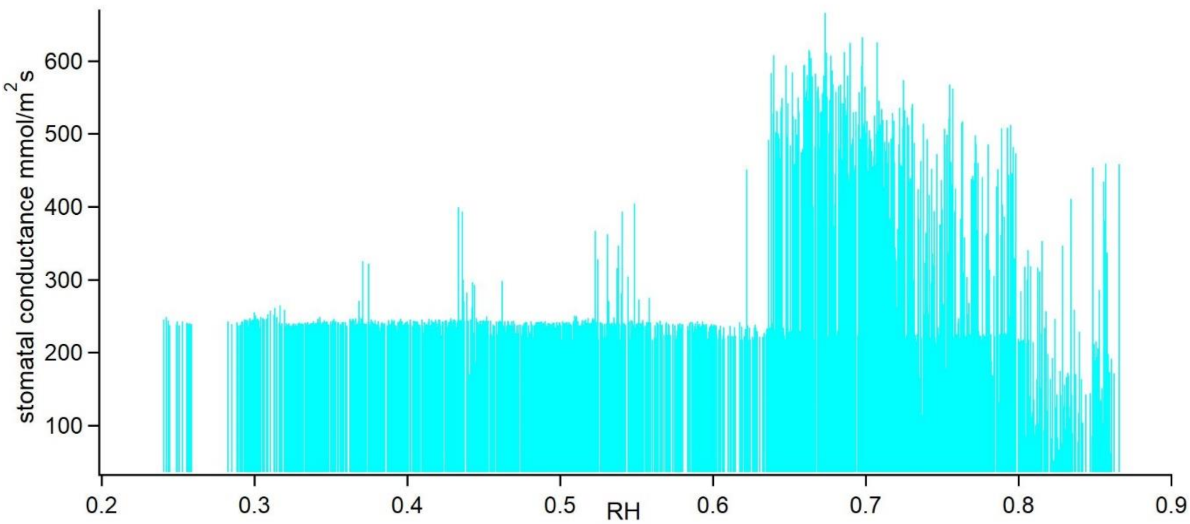


Figure 5: Plot of g_s vs Humidity for Poplar

The stomatal response to humidity can be understood easily as a stomatal response to water loss [4]. Fig 5 depicts that g_s decreases or stomata closes in response to low humidity. Low humidity signifies that the relative moisture in the air is lower than the standard, thus if the leaves were open water will diffuse from (high concentration) the leaf to a lower concentration in the surrounding (transpiration will take place). In order to prevent leaves from drying, closure of stomatal pores takes place.

Abscisic acid is a plant hormone that is synthesized in response to drought conditions and causes the closure of stomata in cases of water scarcity where retaining water in leaves is more essential than carrying out the process of photosynthesis.

3. TEMPERATURE

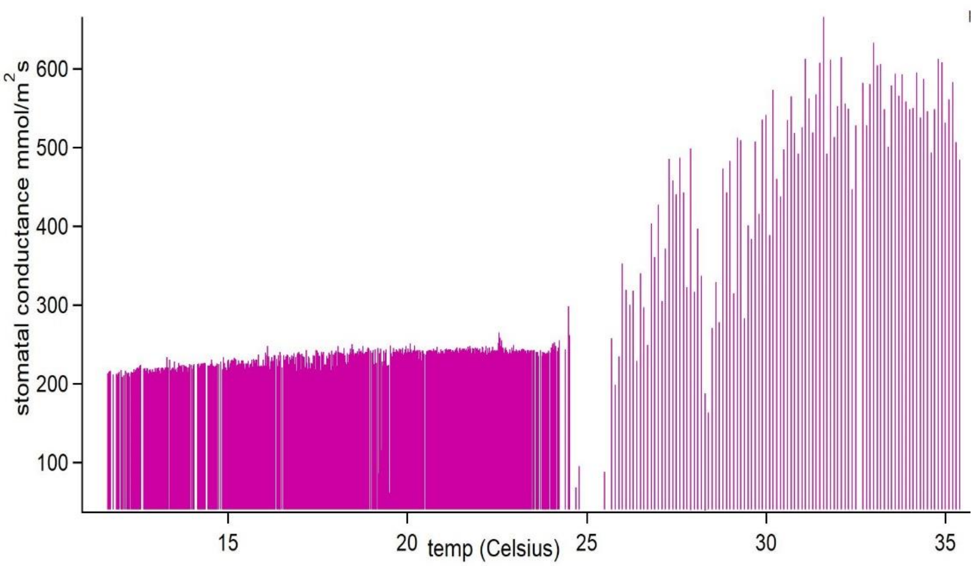


FIGURE 6: Plot of g_s vs Temperature for Poplar

Temperature is one of the most capricious environmental factor as it varies diurnally, monthly and seasonally. It has been gradually increasing over the years, a trend that is expected to continue. High g_s values are observed as the temperature crosses 26 °Celsius i.e. increase in g_s with the increase in Temperature (Fig 6). This result is in corroboration with the controlled experiment done in the growth chamber on poplar (Populus deltoides x nigra) [4]. Increasing the leaf temperature by 10 °C led to a 42% increase in g_s values of poplar as VPD and [CO_2] were kept constant. It was also concluded that the effect of temperature on g_s was predominant at high VPD values. Generally, g_s values drop with increase in [CO_2] or with the decrease in soil water content but it was reported that even at high [CO_2] or low soil water content g_s increased with increase in temperature.

4. LIGHT

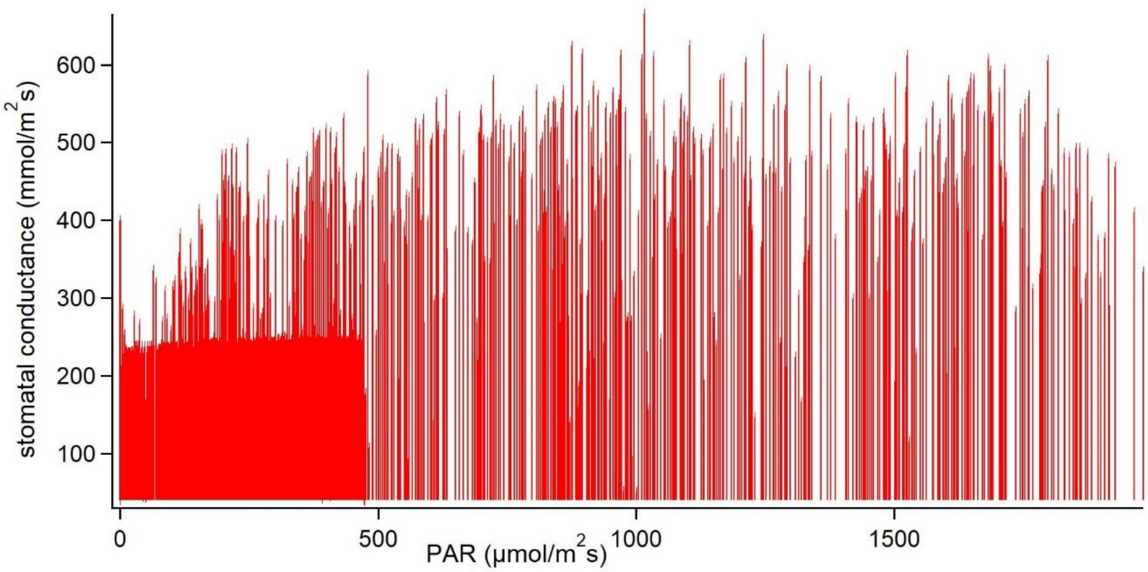


Figure 7: Plot of g_s vs PAR for Poplar

Light positively influences g_s (Fig 7). Light-activated ions pumping into the guard cells is supposed to be the reason for stomata's response to light. There are two separate photoreceptors involved in the response of stomata to light-

- Blue light response - An action spectrum that peaks around 470 nm and is activated by one or more receptors located in the guard cell.
- Red light response - An action spectrum similar to chlorophyll and is sensed by chlorophyll.

With the change in the intensity of light, the stomatal pattern changes. There is an increase in the stomatal index with the increase in light intensity and mature leaves control this response.

5. SOIL MOISTURE

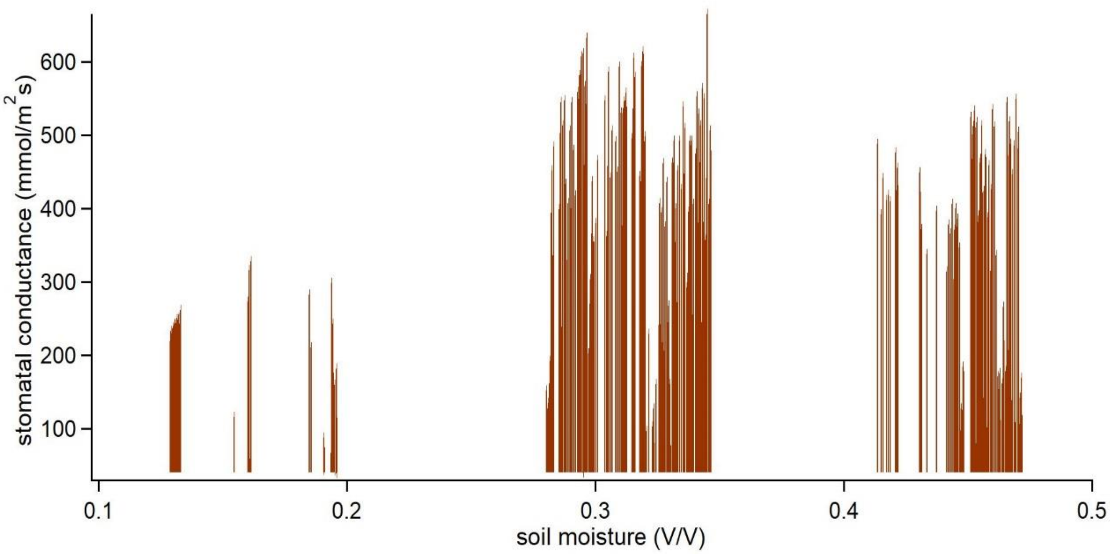


Figure 8: Plot of g_s vs Soil Moisture for Poplar

Soil moisture plays a crucial role in regulating stomatal behavior, growth, and productivity of trees/crops. Low Soil Moisture leads to low g_s to prevent loss of already less available water by transpiration.

Low soil moisture reduces the g_s even more than only elevated CO_2 and temperature does [21]. Trees that already have or are able to a deeper root system are expected to have better survival rates than ones with a more superficial root system as in the coming year's drought events are estimated to increase in terms of both frequency and intensity. [5]

3.2 SEASONAL VARIATION IN STOMATAL CONDUCTANCE VALUES

g_s were hourly-averaged and plotted against the hour of the day to study the seasonal trend of stomatal conductance values. Seasonal variation will occur due to the seasonal change in weather and also the phenology of the leaves as they may expand, age, etc.

3.2.1 Poplar

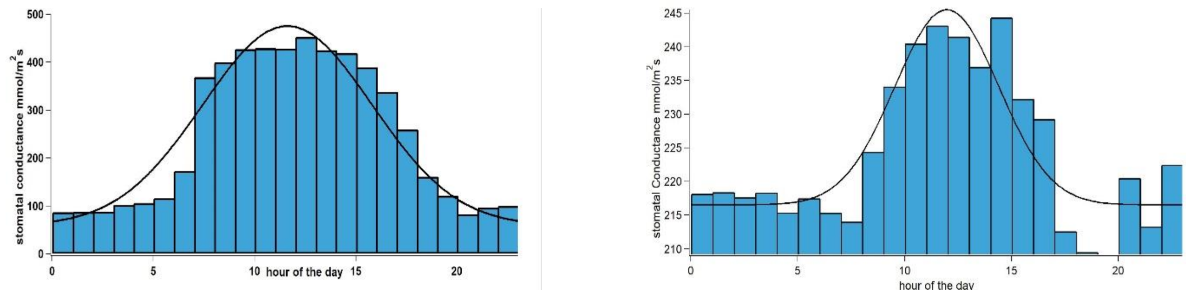


Figure 9: Hourly Averaged g_s values for Poplar monsoon (left) and post-monsoon (right)

3.2.2 Peepal

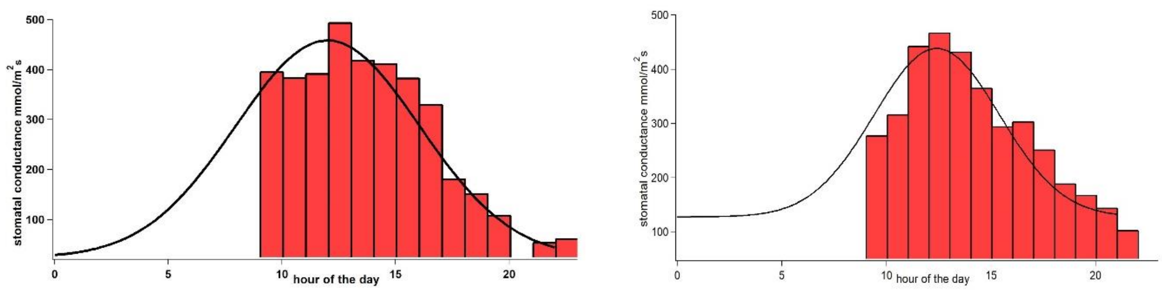


Figure 10: Hourly Averaged g_s values for Peepal monsoon (left) and post-monsoon (right)

For Poplar

During Monsoon, maximum average-conductance was observed during 12 noon and average-conductance range was between 80-450 mmol/m^{2}s. However, the post-monsoon values were between 210-245 mmol/m^{2}s and the maximum average-conductance was observed during 2-3pm.

For Peepal

During Monsoon and post-monsoon maximum average-conductance was observed during 12 noon and average-conductances were in between 50-500 mmol/m^{2}s. Maximum average-conductance was higher for monsoon.

3.3 RESPONSE FUNCTIONS

3.2.1 POPLAR

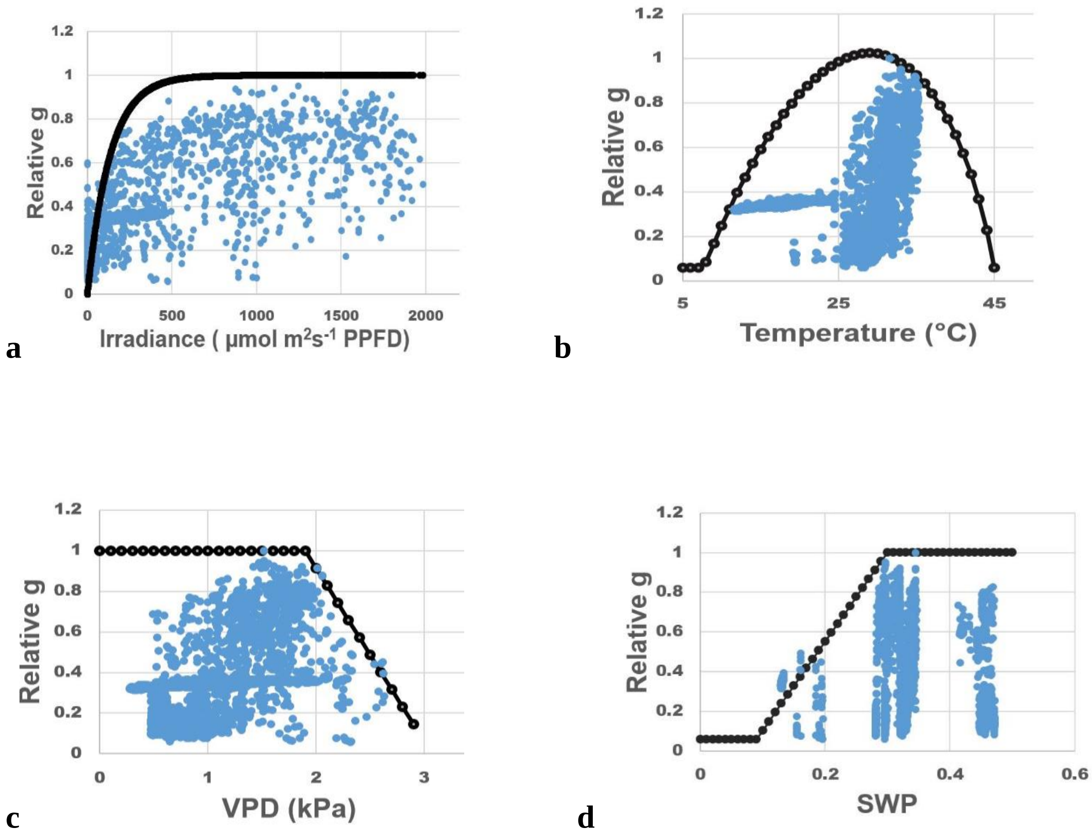
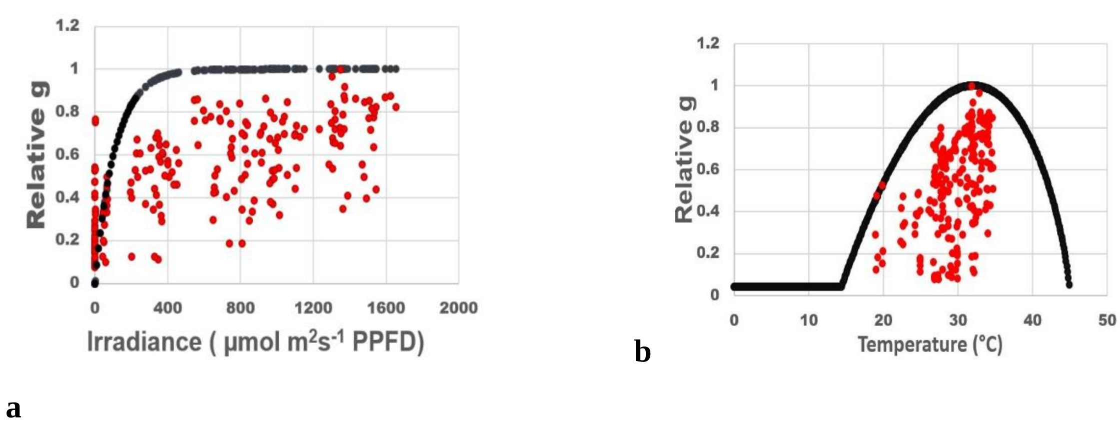
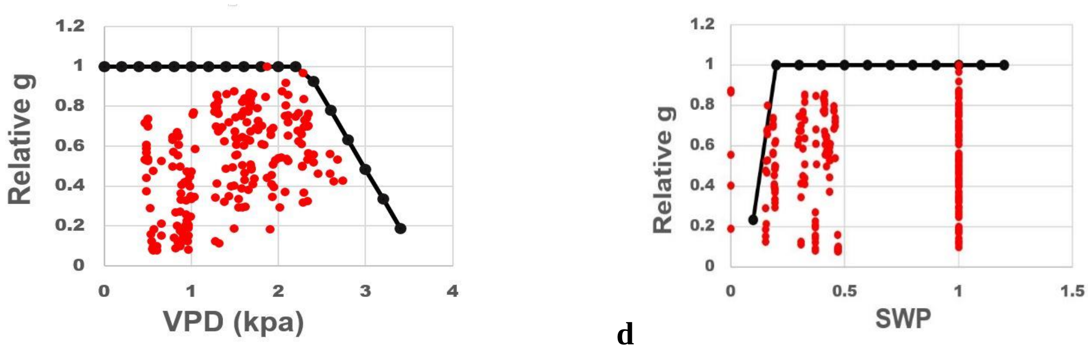


Figure 11: Functions describing the dependence relationship between Relative g and **a** irradiance **b** Temperature **c** VPD **d** SWP

3.2.2 PEEPAL





c **d**

Figure 12: Functions describing the dependence relationship between Relative g and **a** irradiance **b** Temperature **c** VPD **d** SWP

Figure 11 and 12 show the Response functions plotted for Poplar and Peepal.

<u>Interpretation of Response Functions</u> –

As irradiance increases, relative g increases rapidly then reaches a steady maximum of 1 (Fig11a; 12a). With the increase in Temperature, relative g increases but only at optimum Temperature maximum g_s is recorded, it then decreases gradually because at high-temperature leaves tend to shut down its stomata in order to prevent loss of excess water (Fig11b: 12b). VPD is the measure of the drying power of the air. Increase in VPD, causes g_s to decrease above a threshold value (VPD_{max}). The VPD at which minimum relative g is obtained is known as the VPD_{min} (Fig 11c; 12c). Soil Water Potential causes g_s to increase till it reaches a relative stable maximum of 1 (Figure11d: 12d).

FUNCTION	PARAMETERS	UNITS	POPLAR	PEEPAL
	g_{max}	mmol H_2O/m^2s	665.4	629
f_{min}		Fraction	0.06	0.04
f_{light}	α	Fraction	0.008	0.009
f_{temp}	T_{min}	Celsius	0	14
	T_{max}	Celsius	45	45
	T_{opt}	Celsius	26	32
f_{VPD}	VPD_{max}	kPa	1.9	2.3
	VPD_{min}	kPa	3	3.6
f_{SM}	SW_{min}	%	9	8
	SW_{max}	%	30	18

Table 5: Parametrization Table for Poplar and Peepal

3.4 MODEL RESULTS – COMPARISON OF MODELED vs MEASURED g_s

To check the applicability of the model, measured conductance from the leaf porometer were compared with the modeled conductance values that were estimated by the model using the multiplicative algorithm by combining the effects of environmental and phonological factors.

3.3.1 POPLAR

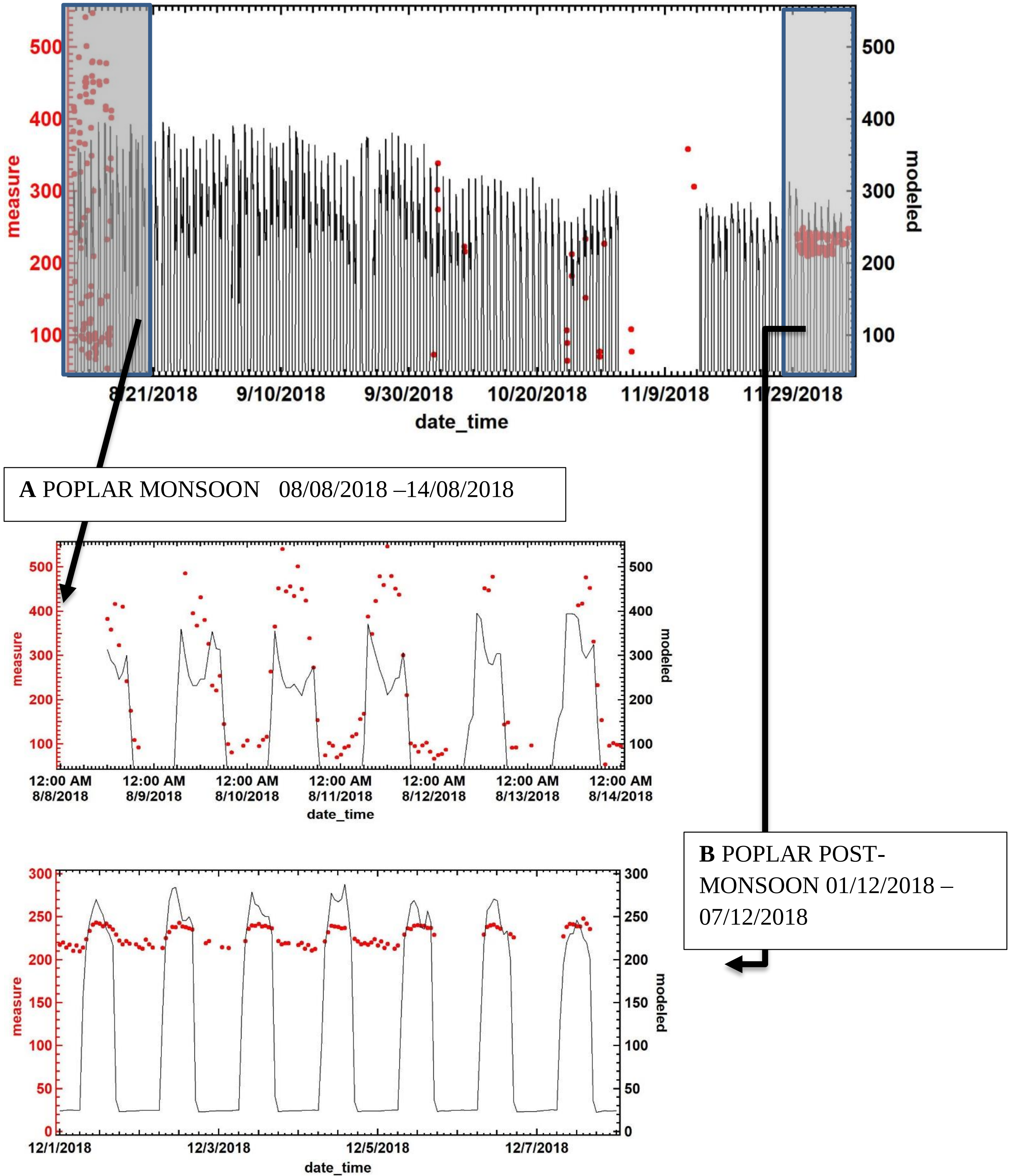
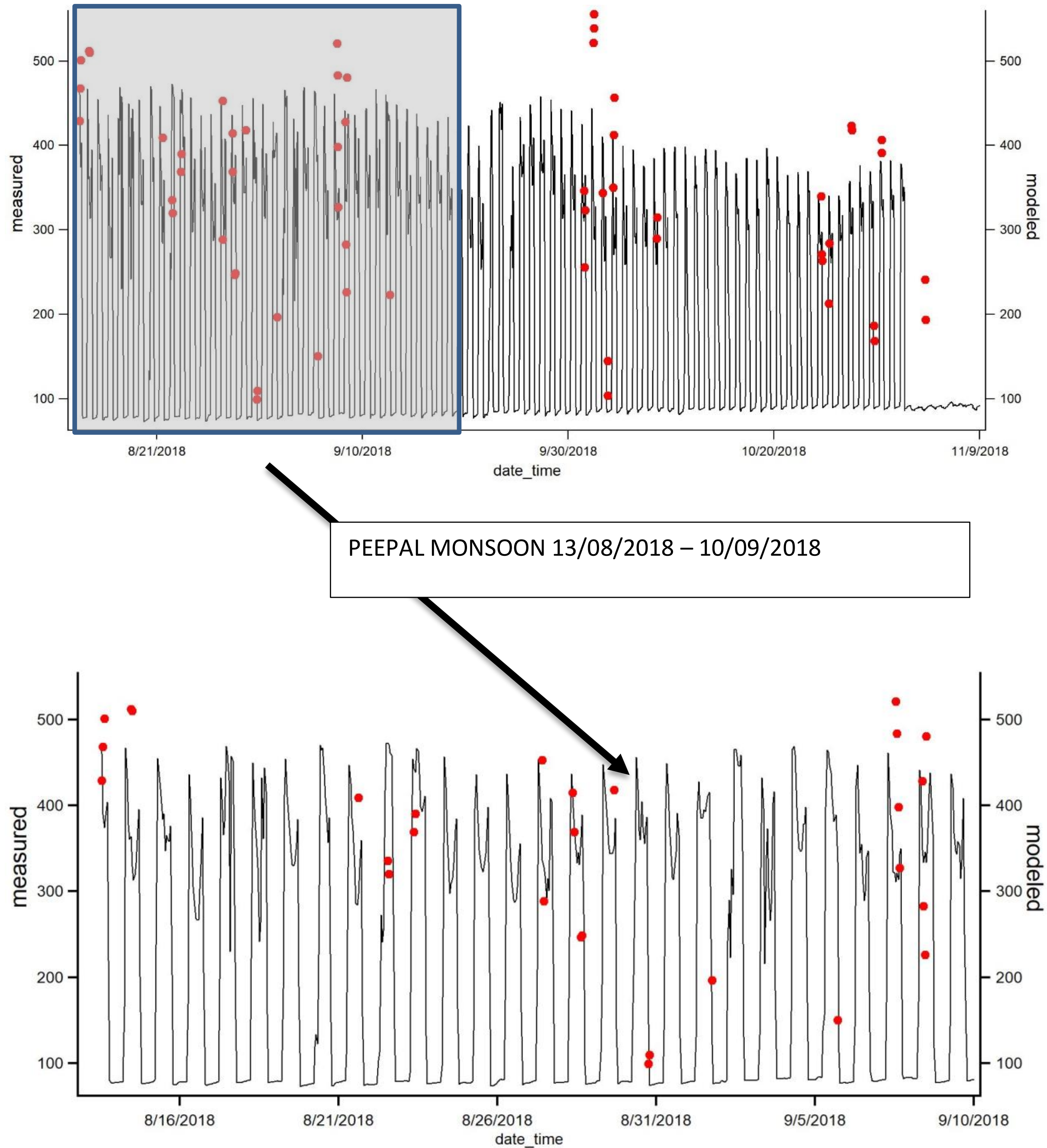


Figure 13: Comparison between modeled and measured g_s values for Poplar. **A** Zoom in plot for Monsoon **B** Zoom in plot for Post-Monsoon

Model underestimated the high g_s values for poplar monsoon whereas the correlation seems fine for low g_s values (Fig 13A).

There is a slight overestimation of the high g_s values for the post-monsoon season and high underestimation of the low g_s values (Fig 13B).

3.3.2 PEEPAL



A

Figure 14: Comparison between modeled and measured g_s values for Peepal. **A** Zoom in plot

The correlation between the modeled and measured low g_s values seems fine. However, the model underestimates few high g_s values.

CHAPTER 4

Conclusion-

Preliminary work to set up DO_3SE model for *Populus Deltoides* and *Ficus Religiosa* was carried out.

CHAPTER 5

Discussion-

Nowadays, modeling is a highly used and applied method for integration, simulation and prediction purpose. DO_3SE model can be employed to estimate g_s values in areas where data of O_3, wind speed, Temperature, humidity, soil moisture, PAR is available.

This model, however, presents the drawback that it assumes that the response of g_s to each environmental factor is independent of each other. External Tree/Plant nutrition is a major determinant of g_s values and can be included in this model to improve its performance. Also, it will be difficult to setup the model for trees in forests and remote areas where availability of meteorological parameters is highly unlikely.

The environmental inputs for the model were detrimental for its better accuracy and also served as the source of errors.

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