Remote Sensing of Leaf Area Index and Primary Productivity

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Lecture - 14
RS of Primary Productivity Methods - SIF

Hi welcome back, so today on the 14th lecture we will continue our discussion with respect to Remote Sensing of Primary Productivity Methods. And with this let us discuss on solar induced fluorescence and the land surface temperature, how they serve as a measure or estimate of primary production.

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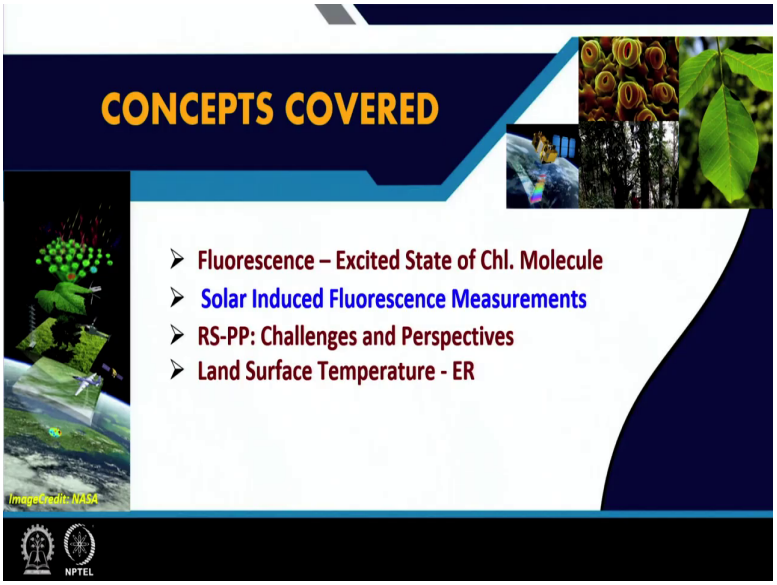

We will cover the four concepts broadly. So, fluorescence we will try to understand how the excited states of chlorophyll molecules helps in understanding the fluorescence. And solar induced fluorescence abbreviated as SIF measurements, how it is actually measured based on remote sensing and also the basis how it originates with respect to the chlorophyll fluorescence.

The 3rd is the relationship between remote sensing and primary production what as the what are the different challenges and perspectives and 4th we will see to cover the land surface temperature and as all of us know this is very important in terms of contributing to estimation

of the respiration or we say the ecosystem respiration ER which goes as an input variable to the calculation of GPP minus ER that we get the NPPR the net primary production of an ecosystem.

So LST calculation provides a basis to estimate the ecosystem respiration that in turn helps us in understanding the respiration term which together with NPP net primary production gives us the gross primary production GPP.

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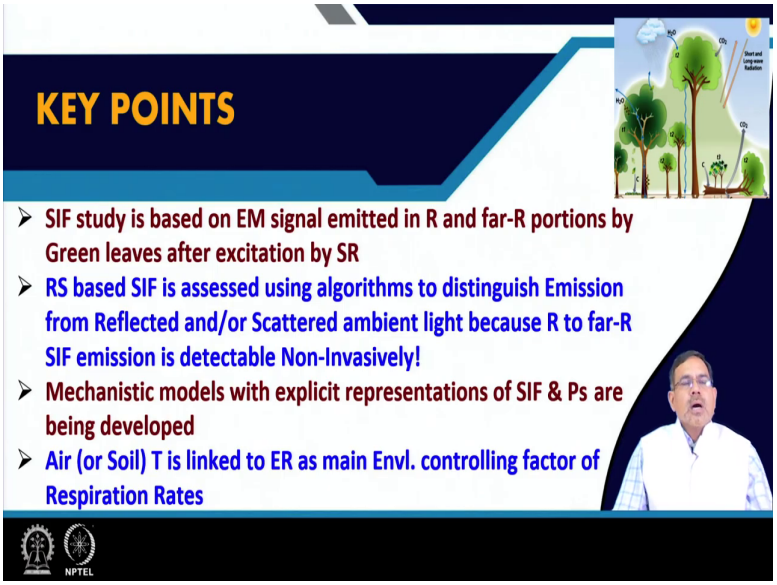

So, this four broad points we will try to cover, the key points are SIF study is based on electromagnetic signals emitted in the red and the far red portions by the green leaves after excitation by the solar radiation.

So, it is very interesting and this signal is very what you say is very less. But let us see how to use this how to capture this signal which is emitted in the red and the far red portions of the green leaves. So, more importantly the green leaves that has the chloroplast and chlorophyll molecules.

So, from there how it is and how much EM signal is emitted. So, that will be measuring or will be studied or estimated under the solar induced fluorescence section. So, second is the remote sensing based solar induced fluorescence is assessed using state of the art algorithms,

to distinguish emission from the reflected and or scattered ambient light because the red and far red SIF emission is detectable noninvasively.

So, it is more important to understand that using the latest or the state of the technology how to distinguish the emission from the reflected and or scattered ambient light ok and particularly in the red and the far red portion. So, this mechanistic models with explicit representation of SIF and photosynthesis are being developed to make very precise estimation of SIF for understanding with respect to the primary production.

And 4th we will try to include our discussion with respect to the temperature or the land surface temperature, which we put as the main environmental controlling factor of respiration rates. That could include the air temperature, soil temperature because it is cumulative when you measure it from a distance in terms of the land surface temperature.

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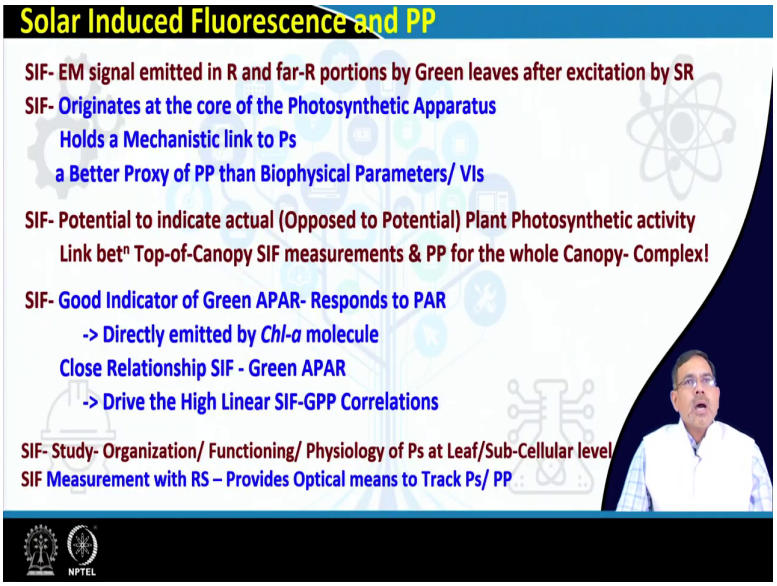

So, now with respect to the SIF solar induced fluorescence and the primary production. So, as we know it is it measures particular the electromagnetic signals which are emitted in the red and far red portions by the green leaves after excitation by the solar radiation. So, solar induced fluorescence originates at the core of the photosynthetic apparatus.

Hence perhaps we understand what is the core of the photosynthetic apparatus in some of our previous lectures we have discussed with respect to the chlorophyll pigment all of you know

the porphyrin ring and you have magnesium and the other what you say components in that. So, and you have the photosystem 1 photosystem 2 the accessory pigments and the pigment which takes or which participate in the process of photosynthesis.

So, a core understanding of the mechanism of photosynthesis and the photosynthetic apparatus helps us in understanding the solar induced fluorescence process. So, this originates at the core of the photosynthetic apparatus and SIF holds a mechanistic link to the photosynthesis are the primary production, because as we can understand it involves the mechanism it involves the mechanics of the photosynthetic apparatus. So, it holds a direct photo mechanistic link with photosynthesis.

And in comparison to other biophysical parameters or such as LAI what we have been discussing or other vegetation indices these serves as a better proxy of primary production. As we can understand because it involves a direct what you said direct measurement of the electromagnetic signals emitted.

So, it serves as a better proxy of the primary production than any or and then the other biophysical parameters are vegetation indices what we have studied because they do a kind of indirect measurement or a proxy or a potential. So but this one SIF that is why is more important because it actually measures what you say EM signals which is emitted in the R and far red portions.

Now, with respect to this solar induced fluorescence it has potential to indicate actual as I mentioned in contrast or in opposed to the potential photosynthetic activity of plants. And therefore it offers a link between the top of canopy solar induced fluorescence measurements and the primary production for the whole canopy ok. So, it offers better link with respect to the top of canopy solar induced fluorescence measurements and the primary production ok for the whole canopy.

But it is not that easy or straight or linear linked it is complex because as we understand the structure is complex the pigment ratio of percentage everything is complex. So, it depends on the pigment concentration the canopy structure and main things, so that adds to the

complexity. Coming to the next key points SIF is a good indicator of green APAR, so green absorbed photosynthetically active radiation because it responds to the PAR.

And directly emitted as we know from the directly emitted by the chlorophyll a molecule the one which participates in the process of photosynthesis are the light reaction and it also drives a kind of high linear relationship or correlation with respect to or with the GPP. So, SIF GPP relationship is very high for the green apparatus and what you say production primary production.

And SIF study because of this it involves the organizational functional and physiological aspects of the photosynthesis at leaf and the sub cellular level. So, it is very important to understand this key points it involves the SIF study involves understanding of organizational functional and physiological components of the photosynthesis, both had the sub cellular level at the antenna pigment or the antenna molecule the chlorophyll a molecule and within the leaf.

So, the photosynthetic apparatus understanding is very important to understand the SIF, then the SIF measurements with remote sensing provides optical means to track photosynthesis and primary production.

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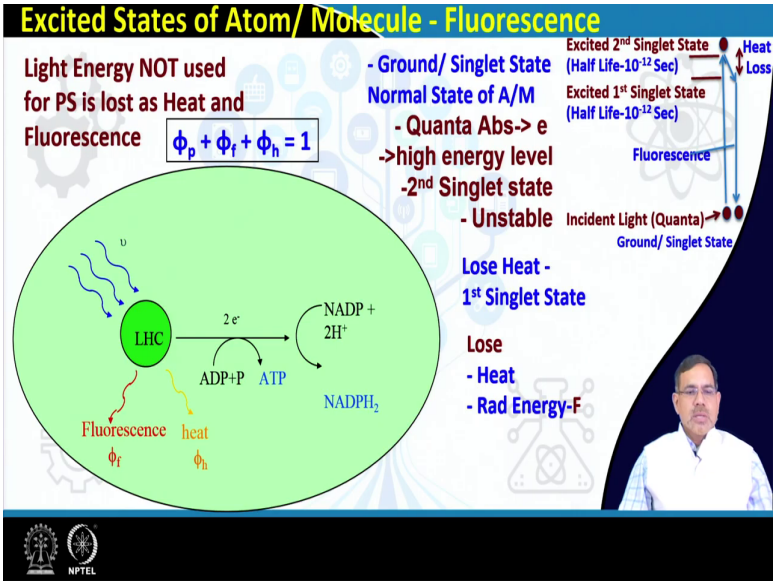

So, how it does? So, if we see this particular figure on the right hand side I try to explain the different excited states of atom or molecule in general. But we can understand it with respect to the chlorophyll molecule here in terms of understanding the concept of fluorescence.

So, look at the diagram the lines drawn on run in terms of the blue color line. So, as we know when a kind of energy or quanta is fallen on the molecule it could be chlorophyll molecule here. So, it the temperature the energy level rises.

So, the energy level rises on absorption of the incident light or we say quanta. So, what happens the ground or the single singlet state of the molecule will observe and get excited. And with respect to higher energy level it will move to a state called excited second singlet state second singlet state which we can see on the top in terms of the molecule moving from a ground singlet to an excited second singlet state.

But this is as we can understand this is at here the energy level is high and that is why it is unstable and it also can be understand with respect to its high on stability with respect to half-life period of 10 to the power minus 12 seconds. So, what it does it would lose some heat to come down to the next excited state that is the first singlet state which is relatively stable, but it is also unstable having half-life period of 10 to the power minus 12.

So, 10 this excited molecular atom we are comparing with we are trying to understand with respect to a chlorophyll molecule. So, it would again loose heat at this state what we have understood in terms of the first singlet state, because here also it is unstable with half-life period of 10 to the power minus 12 second.

So, it will lose either heat or radiation energy to get back to the ground or close to the ground or singlet state. So, these loss of radiation energy or this means of coming back by loosing energy in terms of radiation is what we understand as fluorescence. So, this we say that fluorescence sometime we say fluorescence light. So, coming to the right hand side diagram the light energy not used for photosynthesis is lost as heat and fluorescence.

So, with respect to this epsilon p f and h, p for photosynthesis which is used f for fluorescence and h is for heat. So, this is the sum total of the heat sorry the quanta which is

sum total is one in terms of the total of the quanta with respect to photosynthesis fluorescence and heat.

So, this energy are the light energy meets either of this or this fades, either it is utilized in the process of light reaction photosynthesis or emitted in terms of fluorescence which we may of our main interest or is lost in term in terms of heat.

So, let us understand it very carefully and very clear in mind this is what this emission of light are quanta of energy is defined or is understood in terms of fluorescence. So, if it is induced by the solar light which we mostly use in terms of passive remote sensing then we make a mention of this or tagging of this as solar induced fluorescence.

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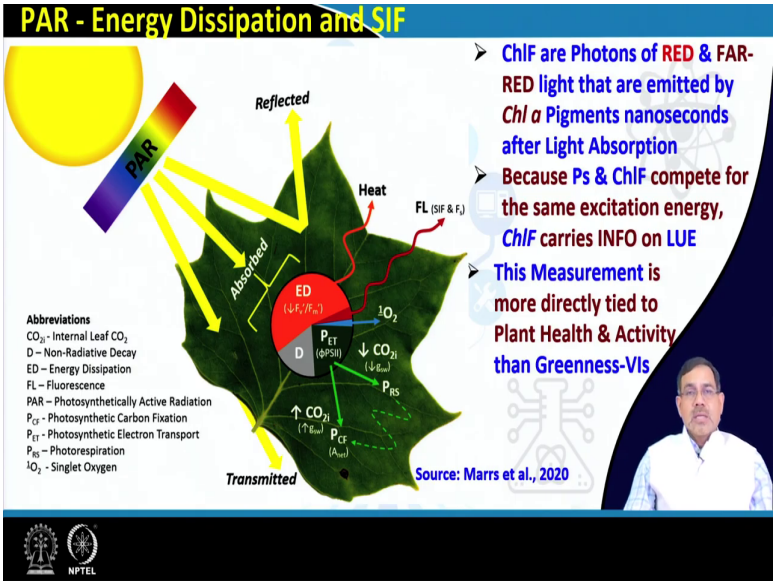

But now let us understand the process with respect to the energy dissipation and the solar induced fluorescence. So, as all of us know the total electromagnetic radiation out of that the one which is absorbed by the photo by the leaf are utilized by the leaf in the process of photosynthesis ok.

So, see saw is in the visible range called PAR range. So, out of that if we see the figure the left hand side arrow yellow arrow refers to transmitted light ok in the PAR region the right hand side arrow refers to the reflected light.

But what is of important to us is the light which is the absorbed light indicated by the middle yellow arrow. And then a kind of Venn diagram that shows the total energy the fate of the total energy and in terms of rate which is the energy dissipation in terms of heat is taking a measure chunk. So, measure chunk of this APAR or we say the absorbed photosynthetically active radiation APAR is being lost as heat.

So, just below that another curve means what you say curvy arrow curve arrow indicates the FL that is for fluorescence and it is a very less portion of the total light it is very less and we know the other things like in terms of the PET and the photosynthetic electron transport photosynthetic carbon fixation photorespiration. So, in all this processes some amount of the absorbed energy is utilized and DA kind of non-radiative decay that is not of our concern in this discussion.

So, we are here concerned with the part of energy which is emitted in term emitted and from this diagram it is very clear in our mind that it is very less, the amount of light emitted in terms of a fluorescence is very less.

So, solar induced fluorescence is either includes is included in that. So now, coming to chlorophyll fluorescence, so chlorophyll fluorescence are photons of red and far red light that are emitted by chlorophyll a pigments nanoseconds after light absorption.

So, I just try to put it in terms of words the chlorophyll flow fluorescence are photons of red and far red light that are emitted by the chlorophyll a pigments just after or you say in terms of nanoseconds of the light absorption. Because the photosynthesis and chlorophyll fluorescence compete for the same excitation energy this is the key actually how it forms the basis in terms of in terms of measuring using remote sensing.

So, the basis is because the photosynthesis and chlorophyll fluorescence compete for the same excitation energy this chlorophyll fluorescence carries information on the light use efficiency. So, it is dependent on the light so and it both this photosynthesis and chlorophyll they compete for the same energy same light. So, that is why it carries information with respect to the yellow carries information on the light use efficiency.

So, this measurement is more directly tied to plant health and activity than the greenness which is represented in many vegetation indices. So, this is that is why we have been discussing as a more direct measurement unlike the other biophysical variables or the vegetation indices. So, SIF is a direct measurement.

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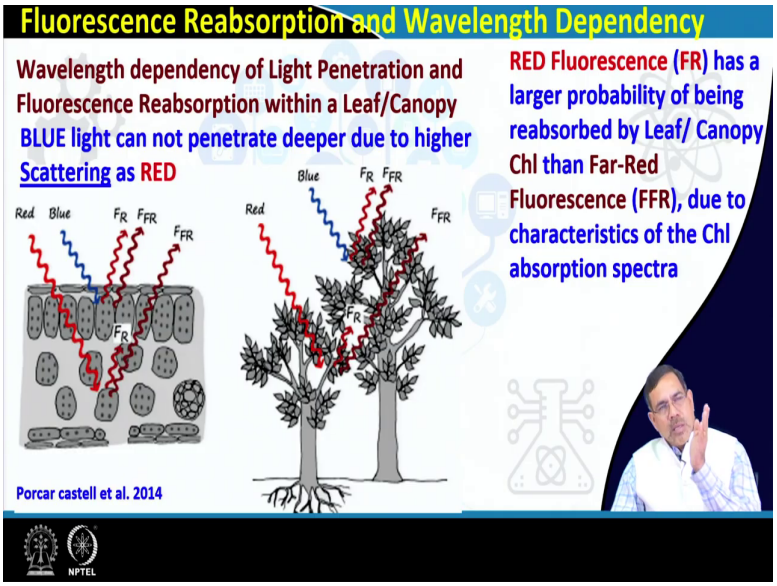

So, in this particular slide I try to discuss with respect to the fluorescence reabsorption and the wavelength dependency. Look at the diagram very clear taken from this particular publication which has been mentioned below. So, wavelength dependency of light penetration and fluorescence reabsorption within a leaf and canopy, but we need to understand here with respect to red light blue light and also the far red fluorescence ok.

So, blue light cannot penetrate deeper as we can see in terms of the cellular space in a within a leaf in a schematic diagram. So, blue light as we know cannot penetrate deeper because of higher scattering. So, as we know blue light scatters most that is why what you say color of the sky and a many more things we see and link to that. So, blue light cannot penetrate deeper due to higher scattering as red

Now, see with respect to the leaf level or cellular level and the leaf canopy level with respect to the right hand side figure. So, the red fluorescence abbreviated as FR has a larger probability of being reabsorbed. So, we can see the curve arrow with respect to red color

arrow for red light ok and which is being reabsorbed by the leaf canopy chlorophyll than the far red fluorescence FFR due to characteristics of the chlorophyll absorption spectra.

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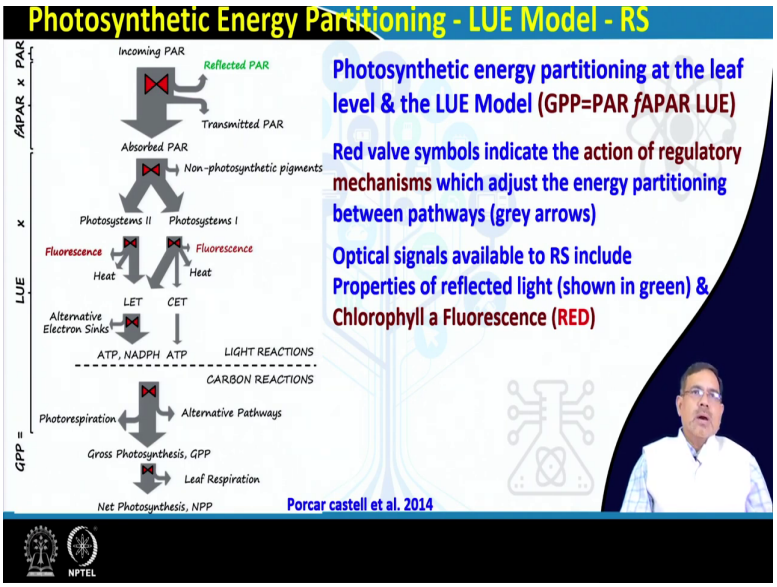

So, in terms of the photosynthetic energy partitioning and as we understood this gives a clue on the LUE. So, LUE based inference what you say derived and utilized in the remote sensing based SIF estimate. So, in this particular diagram again taken from the same publication it is very clear that it is based on a production light used efficiency based what you say algorithm.

So, photosynthetic energy partitioning at the leaf level and the LUE model. So, GPP is equal to or a function of PAR fraction of APAR and LUE and look at the right hand side diagram and what I want you to emphasize on is that the kind of partitioning with respect to incoming PAR then the arrow becomes gray arrow becomes little narrow. Because some part is either reflected in terms of PAR or transmitted in terms of PAR what we have discussed in the previous diagram with respect to a leaf figure.

So, then whatever is left is the absorbed PAR and that also meets 2 pairs in terms of going to photosystem 1 or by the photosystem 1 and photosystem 2 and some is again getting with respect to non-photosynthetic pigments. So, here what is important is in terms of photosystem

2 and photosystem 1 where the excitation and all fluorescence things happen as we understand.

So, look at the red arrow small arrow with valve symbol ok. So, that is what is the fluorescence and look at the quantity so and in the top we have another green text reflected PAR. So, these are the 2 things the reflected PAR and fluorescence which is written in the red text. So, these are the 2 things which are measured by the satellite.

So, till date we know more we have discussed a lot with respect to the PAR, photosynthetically active radiation which is in the forefront, because most of the light means that is at the step 1.

But here the optical signals available to remote sensing include properties of reflected light that is shown in green and important in the chlorophyll a fluorescence that is shown in red. So, this is what we need to understand as per as the photosynthetic energy partitioning in terms of LUE modeled based RS is or remote sensing is concerned.

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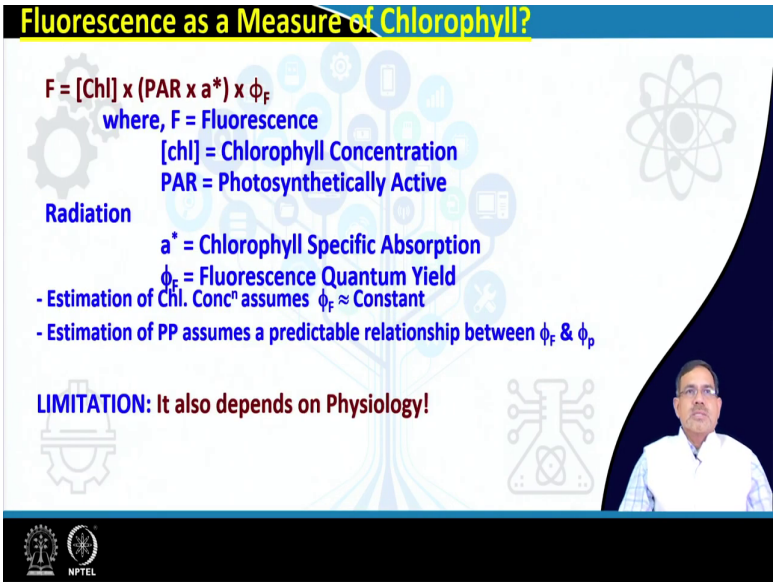

So coming to the fluorescence which is a measure of chlorophyll, so look at this particular equation the F stands for fluorescence and chlorophyll concentration represented by Chl PAR we know photosynthetically active radiation, a star is a chlorophyll specific absorption.

So, that is that could vary from species to species and also from different position season and many other things and a kind of psi F is the fluorescence quantum yield ok. So, fluorescence is important in terms of a measure of chlorophyll, but as we know it depends on the physiology.

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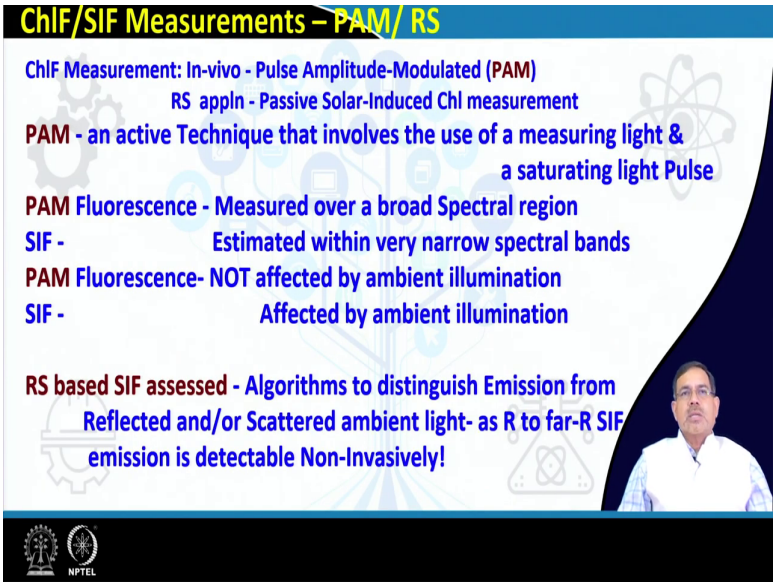

Coming to the measurement protocols friends in terms of the chlorophyll measurements in vivo a lab condition it is measured with respect to pulse amplitude modulated principle. But in remote sensing application particular as we know for passive SIF (Refer Time: 25:22) which is a passive based chlorophyll measurement or SIF. So, PAM the pulse amplitude modulated which is an active technique that involves the use of a measuring light and a saturating light pulse.

And this in terms of PAM fluorescence measured over a broad spectral region, whereas SIF is estimated within a very narrow; that means, red and the far red part of the electromagnetic spectrum. The PAM fluorescence is not affected by ambient illumination, whereas the SIF based fluorescence measurement is affected by ambient illumination.

So, that is the measure difference between PAM which is a lab based measurement protocol of chlorophyll fluorescence, but the moment we come to the SIF which is a ecosystem based

and based on the satellite which is of few 100 kilometers from top that in that measures the solar induced fluorescence.

So, this is the major difference in terms of the measurement protocols and coming to how exactly the remote sensing based SIF is assessed. So, it is assessed based on the state of the art algorithms to distinguish emission ok. So, it distinguishes emission from the reflected and or the scattered or ambient light. So, reflected and the scattered is differentiation as the red to the far red SIF emission is detectable using detectable because it is in it follows a noninvasive principle ok.

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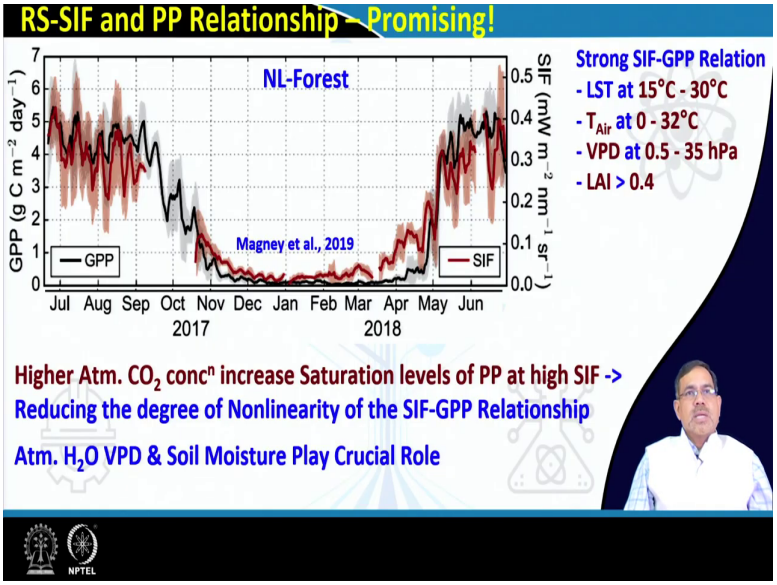

So, this relationship the so lot of algorithms have been developed and you have the SIF solar induced fluorescence. Now the solar induced fluorescence are the maps are related or correlated with respect to GPP. And look at one a correlation with respect to a needle leaf forest published by Magney et al and 2019 on y prime it is GPP on x prime sorry on y axis it is GPP on y prime axis it is SIF and corresponding units.

And you can well appreciate that this GPP is very well matching with the SIF solar induced fluorescence. But this relationship is a looks to be strong, but they are dependent on many factors such as the optimal kind of relationship or correlation are obtained or seem to be obtained when the land surface temperature is between 15 to 30 degree centigrade.

The, air temperature is between 0 to 32 degree centigrade the vapor pressure deficit of water or water vapor deficit is between 0.5 to 35 hecta Pascal and leaf area index should be preferably more than 0.4.

So, these are the well or optimized conditions and we get a very strong relation as we understand, because the measurement the SIF emission signal is very small we know and we need to do a very optimized measurement based on the state of the art algorithms available and they all depend with respect to the what you say the canopy arrangement or canopy structure the pigment concentration and things like that and also the atmospheric conditions.

So, this is very important to get a strong SIF GPP correlation. So, higher atmospheric carbon dioxide concentration increase the saturation levels of primary production at high SIF level. So, that is why it reduces the degree of nonlinearity of the SIF GPP.

So, it is always better to have a linear relations as much as possible, so that extrapolation to a broader region could be done easily. So, atmospheric water vapor deficit and soil moisture can play crucial role.

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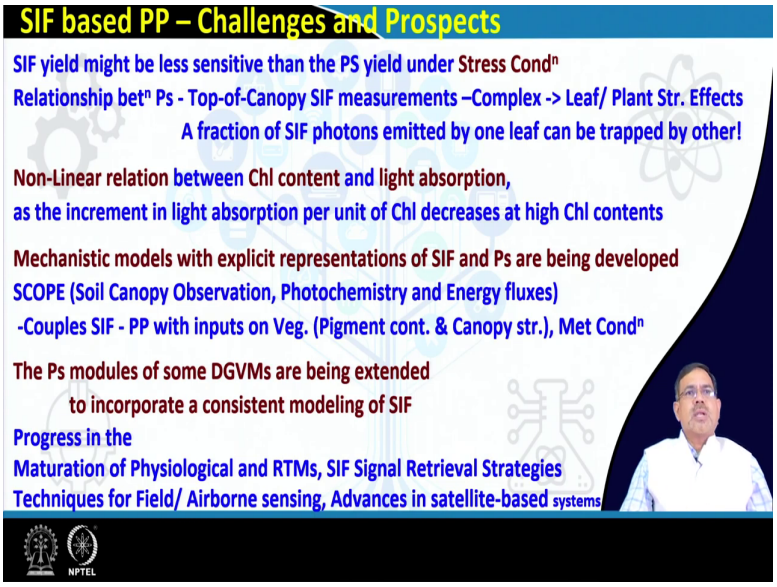

So, the challenges and prospects as we have been discussing SIF yield might be less sensitive than the photosynthesis yield under stress condition. And relationship between the photosynthesis that is the top of canopy solar induced fluorescence measurements could be

complex as we know. Because of leaf and plant structure effects and a fraction of SIF photons emitted by one leaf can also be trapped by other that also needs to be understood.

So, in a complex canopy structure, so some fraction of the SIF photon which is emitted by one leaf may also be trapped by the nearby or adjoining leaf. So, that also has to be kept in mind. So, this non-linear relation between chlorophyll content and light absorption as the increment and in light absorption per unit chlorophyll decreases at high chlorophyll content.

So, this mechanistic models with explicit representations of solar induced fluorescence and photosynthesis are being developed one of them is a SCOPE. So, that is expanded in terms of soil canopy observation photochemistry and energy fluxes and it couples the SIF and primary production with inputs on many vegetation variable including the pigment concentration, the canopy structure, mechanical conditions and things like that.

So, the photosynthesis modules in many of these what you say DGVMs are also being extended in these days in advance research. What happens the photosynthesis modules are being modified or extended in lot of vegetation or dynamic vegetation models DGVMs to incorporate a consistent modeling of SIF. So, SIF component is getting integrated into the DVMs.

But in future many things are going to happen progress progresses in terms of maturation of physiological and radiative transfer models, say SIF signal retrieval strategy techniques for field and airborne sensing and advances in terms of satellite based systems are in process and in progress. So, they will they are these are the major what you say challenges and prospects as for as the solar induced fluorescence based primary production is concerned.

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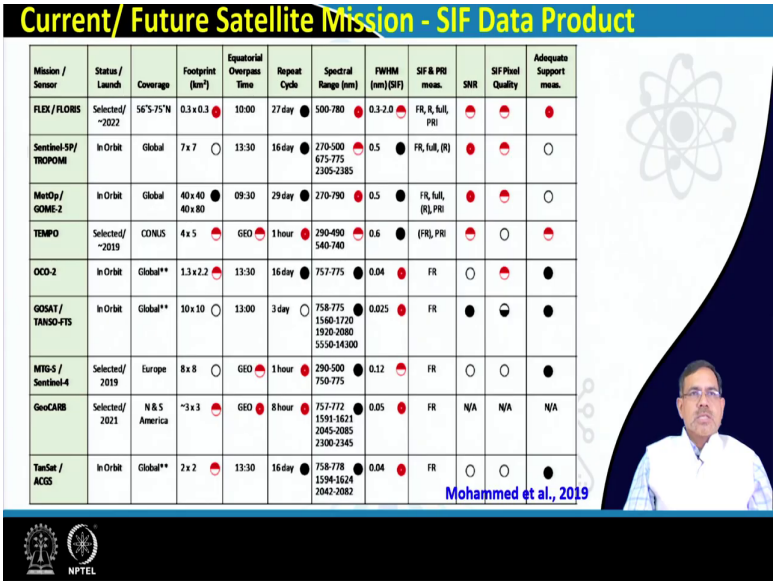

Mission / Sensor	Status / Launch	Coverage	Footprint (km²)	Equatorial Overpass Time	Repeat Cycle	Spectral Range (nm)	FWHM (nm) (SIF)	SIF & PRI meas.	SNR	SIF Pixel Quality	Adequate Support meas.
FLEX / FLORIS	Selected/ ~2022	56°S-75°N	0.3 x 0.3	10:00	27 day	500-780	0.3-2.0	FR, R, full, PRI			
Sentinel-5P/ TROPOMI	In Orbit	Global	7 x 7	13:30	16 day	270-500 675-775 2305-2385	0.5	FR, full, (R)			
MetOp/ GOME-2	In Orbit	Global	40 x 40 40 x 80	09:30	29 day	270-790	0.5	FR, full, (R), PRI			
TEMPO	Selected/ ~2019	CONUS	4 x 5	GEO	1 hour	290-490 540-740	0.6	(FR), PRI			
OCO-2	In Orbit	Global**	1.3 x 2.2	13:30	16 day	757-775	0.04	FR			
GOSAT / TANSO-FTS	In Orbit	Global**	10 x 10	13:00	3 day	758-775 1560-1720 1920-2080 5550-14300	0.025	FR			
MTG-S / Sentinel-4	Selected/ 2019	Europe	8 x 8	GEO	1 hour	290-500 750-775	0.12	FR			
GeoCARB	Selected/ 2021	N & S America	~3 x 3	GEO	8 hour	757-772 1591-1621 2045-2085 2300-2345	0.05	FR	N/A	N/A	N/A
TanSat / ACGS	In Orbit	Global**	2 x 2	13:30	16 day	758-778 1594-1624 2042-2082	0.04	FR			

So, there are lot of satellites and you can refer to this particular paper and this list can be more elaborated.

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So, we will get back to the references in terms of the 3 review papers. So, we have used for this discussion and making the slides.

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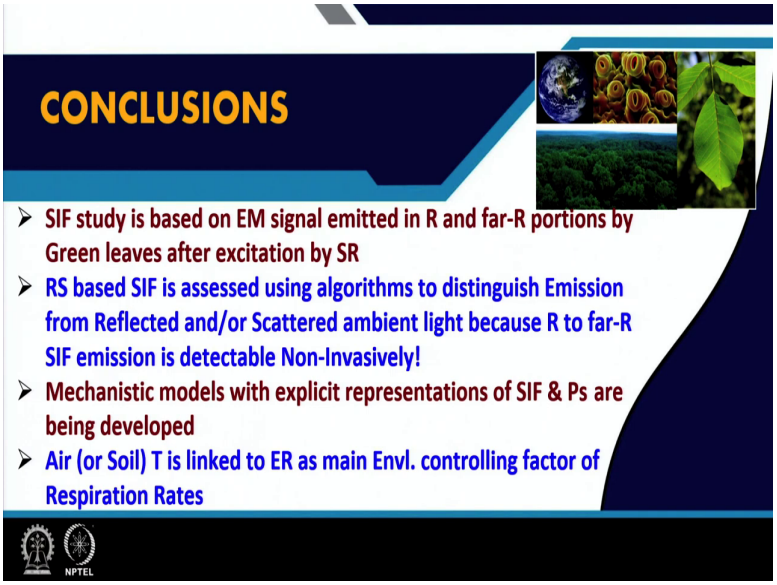

And the conclusions which is again a mirror image of the key points. So, we need to understand and discuss more on them.

Thank you very much.