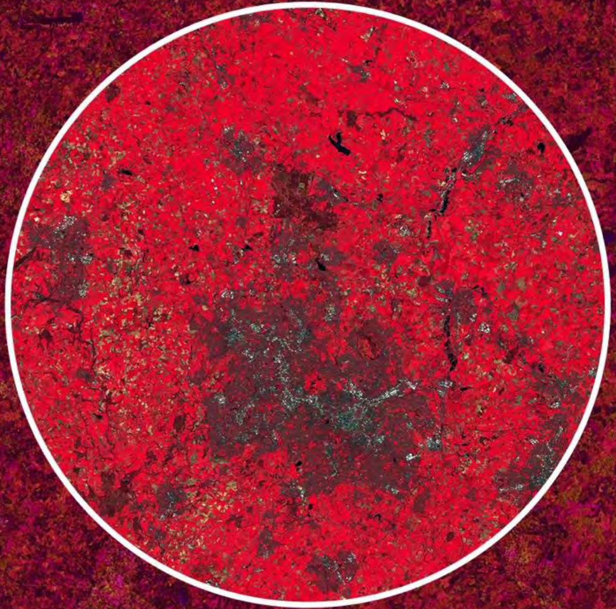
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF LEICESTER

esa

→ 8th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

10–14 September 2018
University of Leicester | United Kingdom



Monitoring Vegetation in a Changing Climate

Gregory Duveiller

14/09/2018

European Commission | Joint Research Centre (JRC)

Objectives…

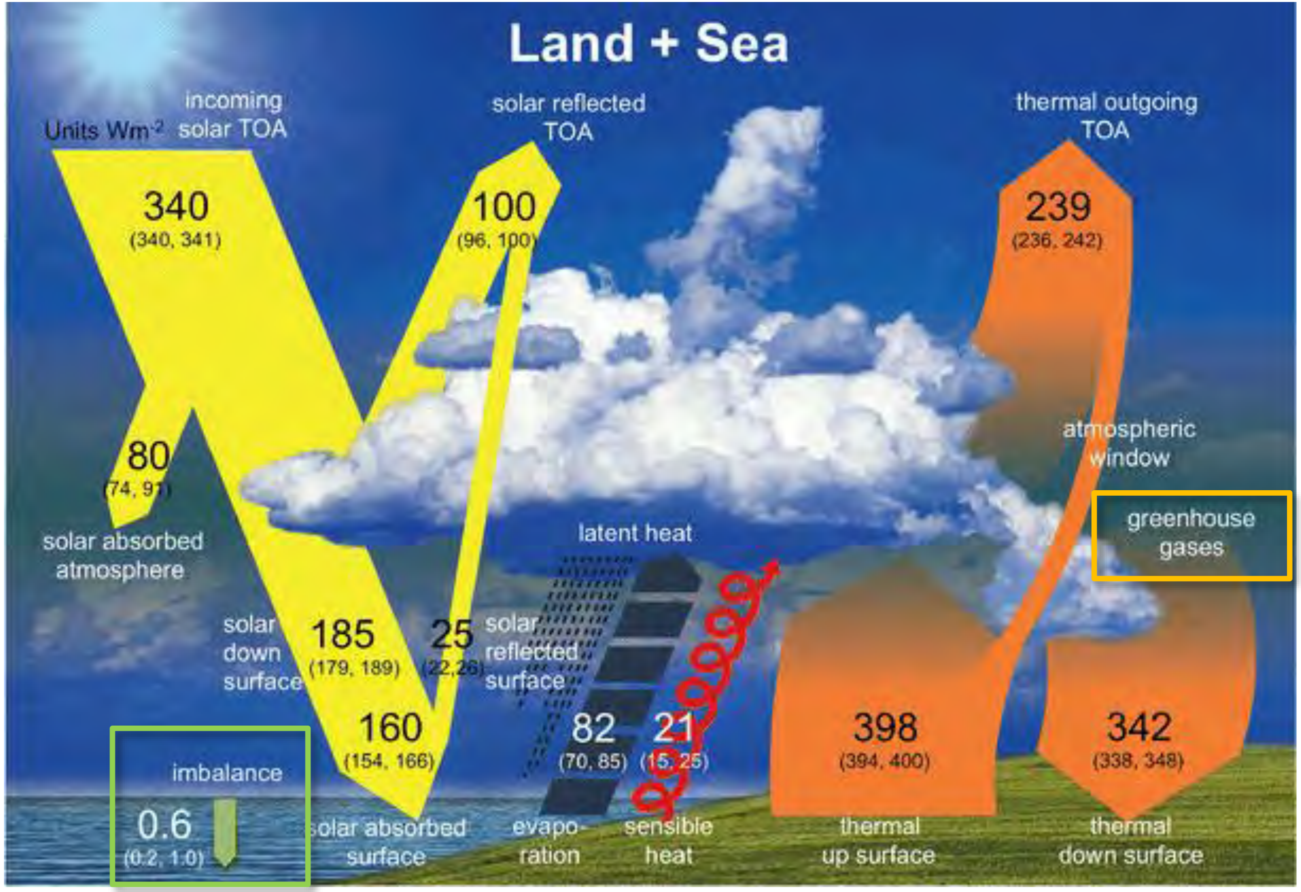
To give a (brief) overview of:

- The type of questions we can address in this subject
- The type of variables we can measure/estimate from satellite EO

  (and which are useful for this subject)
- The type of tools we have at hand
- The type of methods we can use/develop

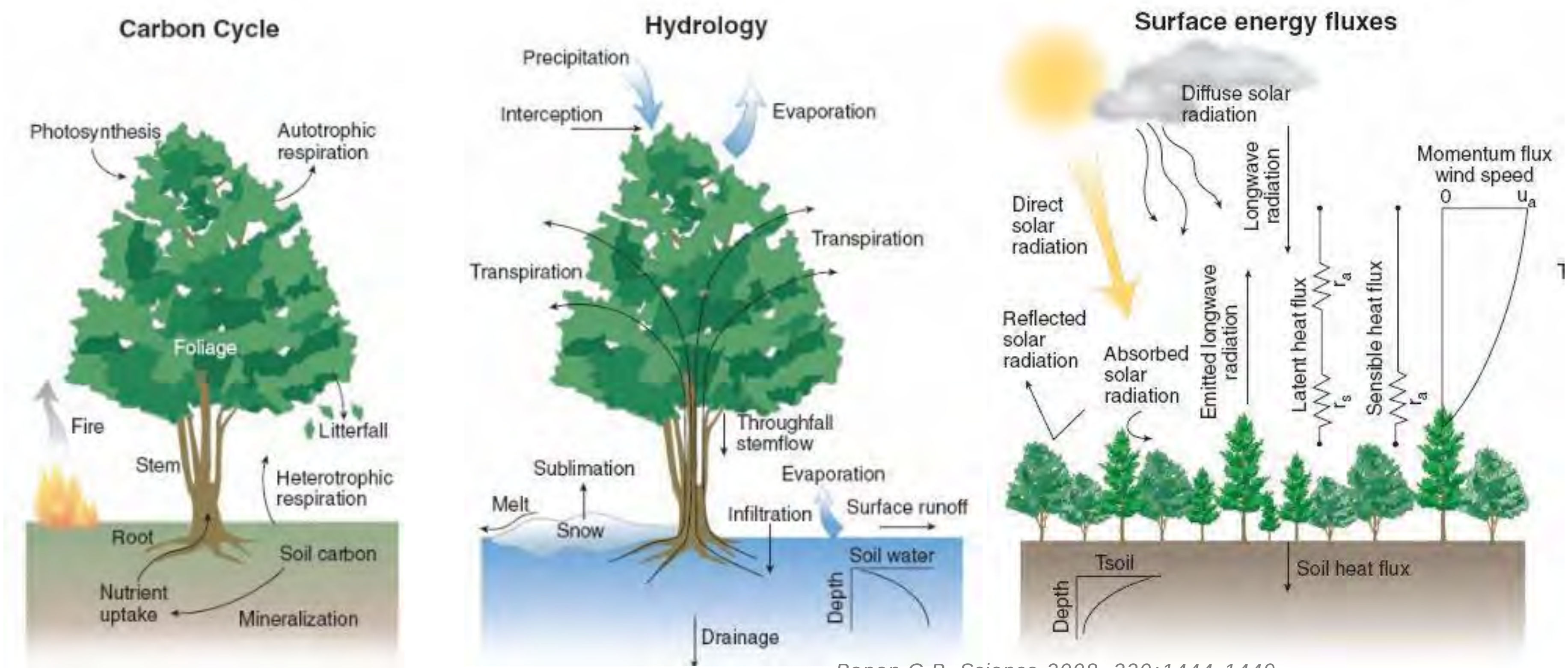
Why/how is the climate changing?

The Global Energy (im)balance



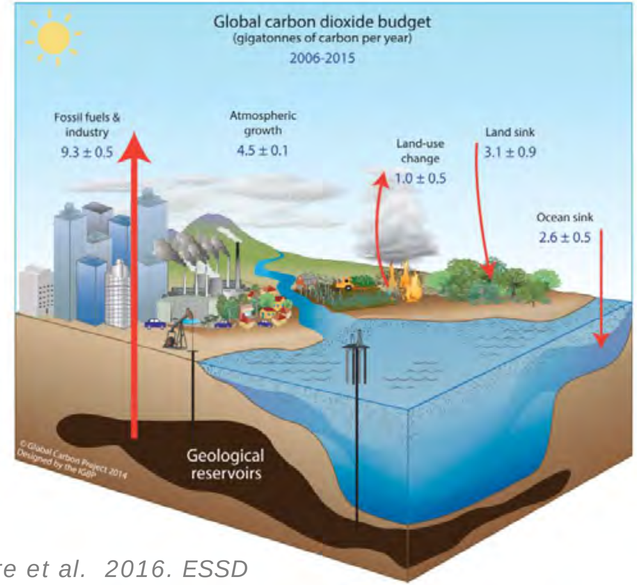
Wild et al. 2015. Clim. Dynamics

Vegetation interacts with climate in various ways



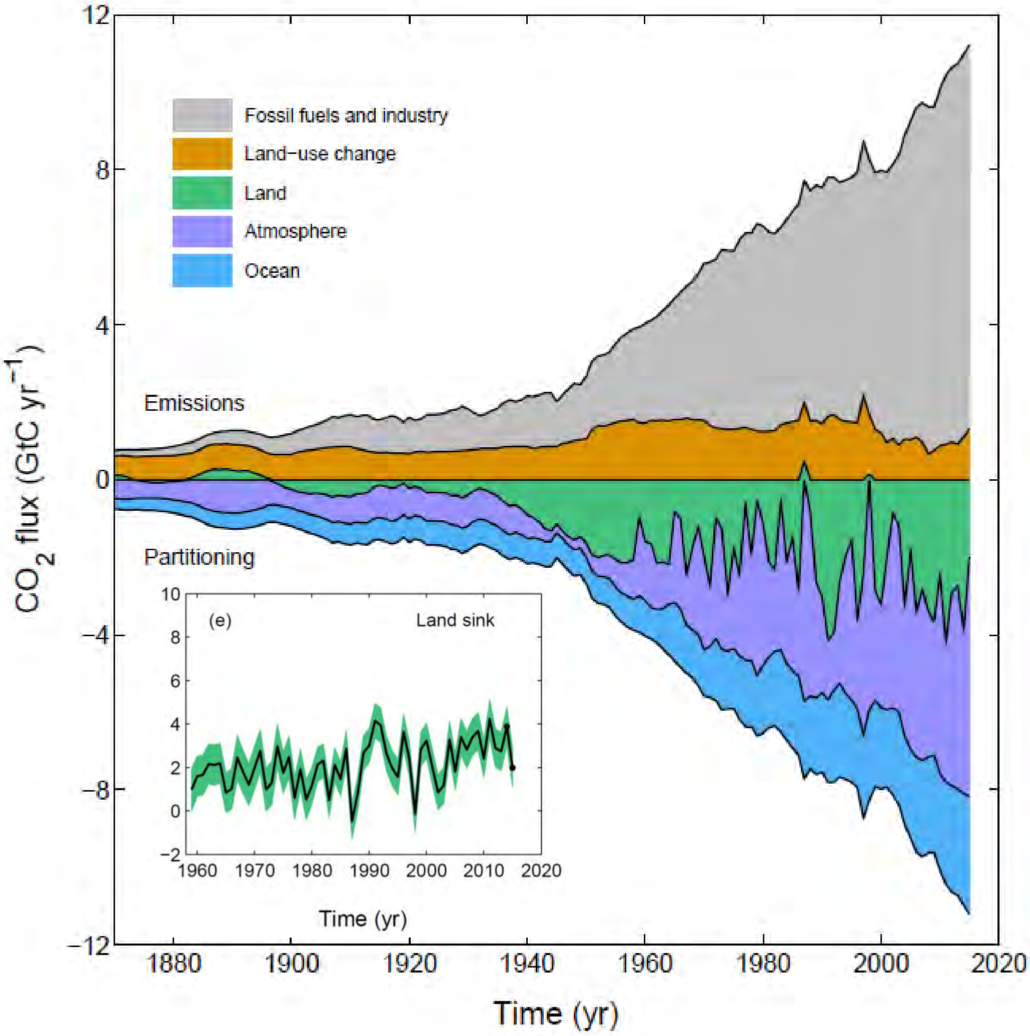
Bonan G.B. Science 2008, 320:1444-1449

Carbon fluxes



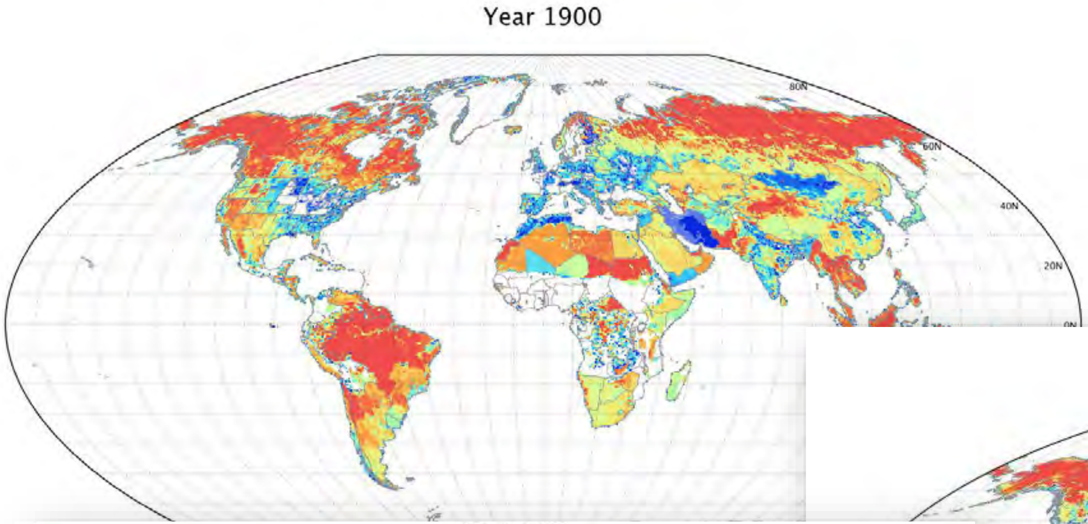
Le Quere et al. 2016. ESSD

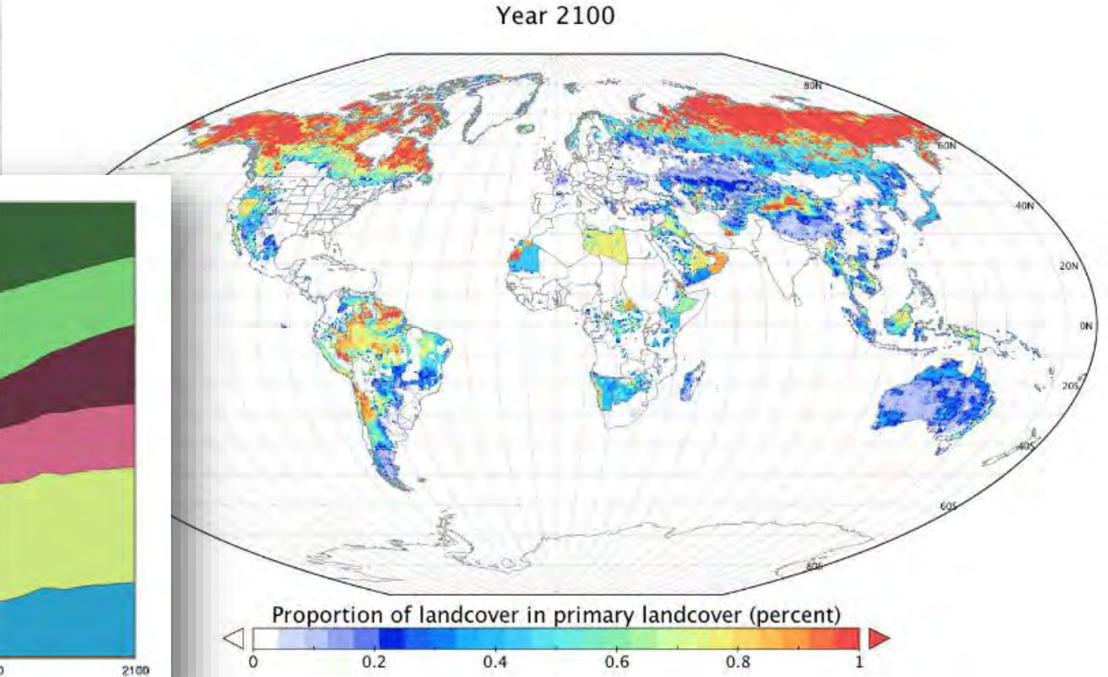
Terrestrial vegetation is the most variable and uncertain component in the global carbon balance

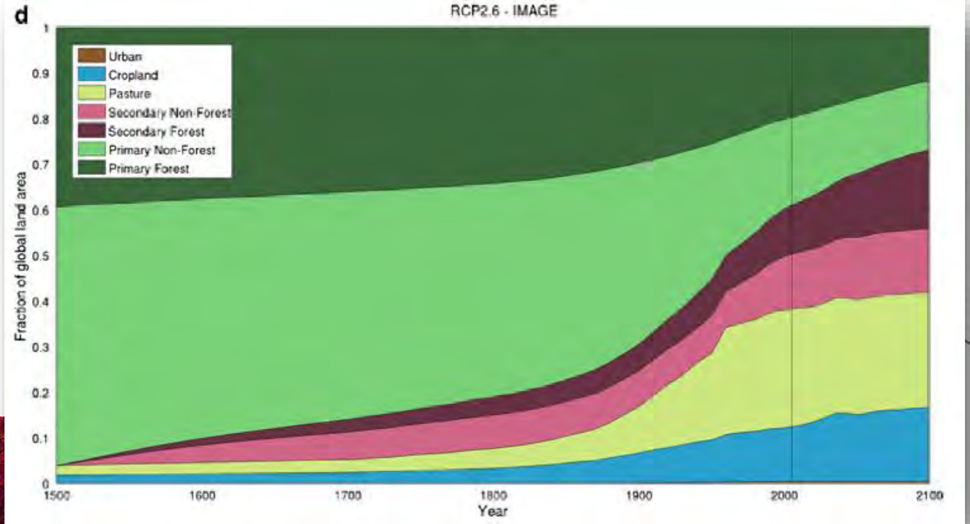


The land is changing …

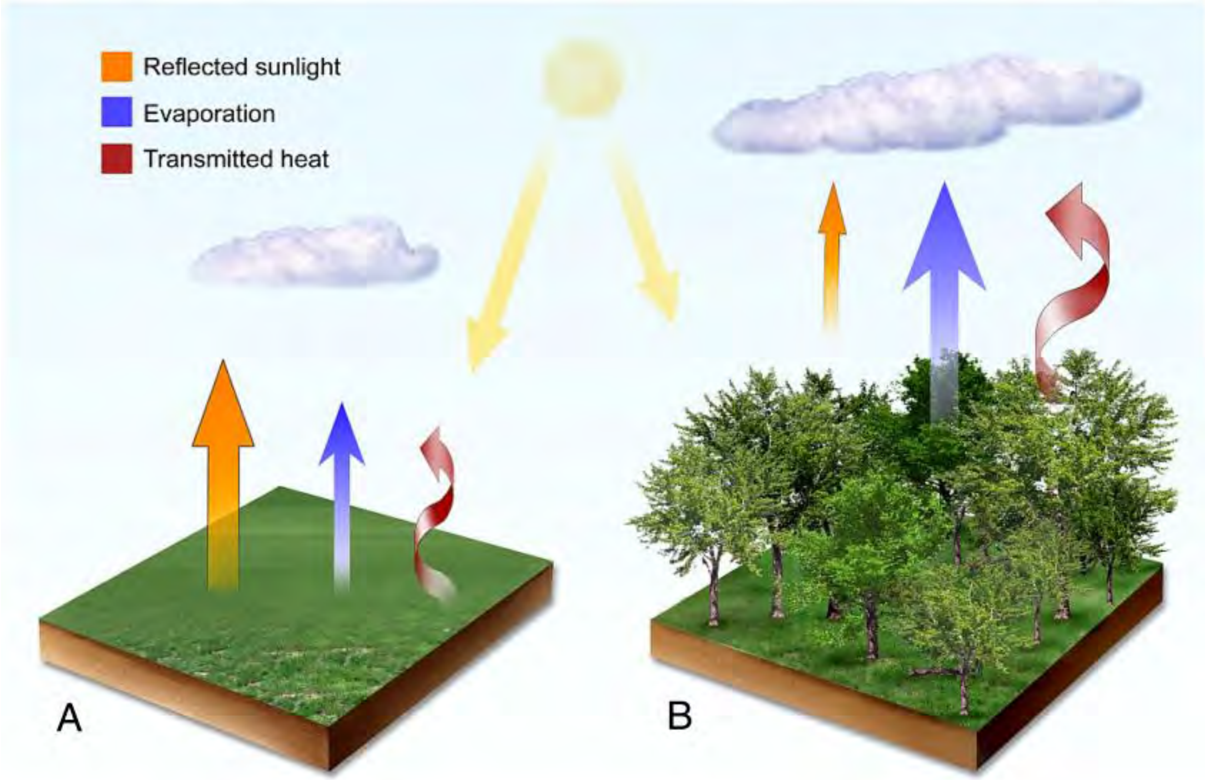
G. C. Hurtt et al 2011. Clim. Change







Land cover changes also has local biophysical impacts

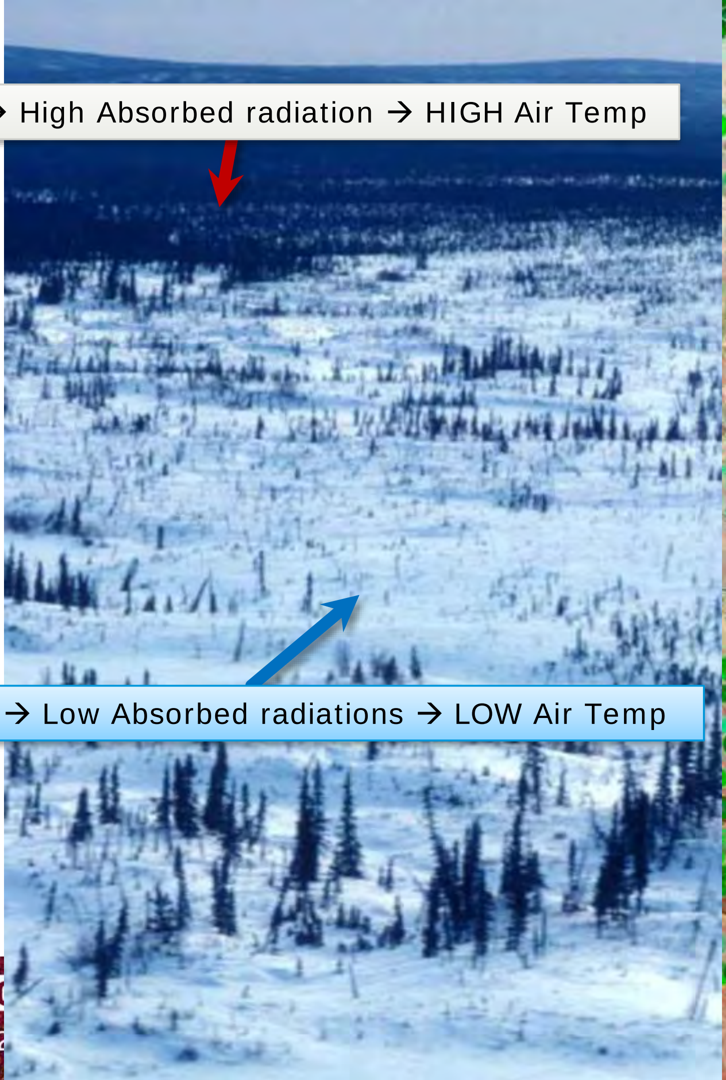


Source:

Jackson, R. B., Randerson, J. T., Canadell, J. G., Anderson, R. G., Avissar, R., Baldocchi, D. D., … Pataki, D. E. (2008). Protecting climate with forests. Environmental Research Letters, 3(4)

ALBEDO

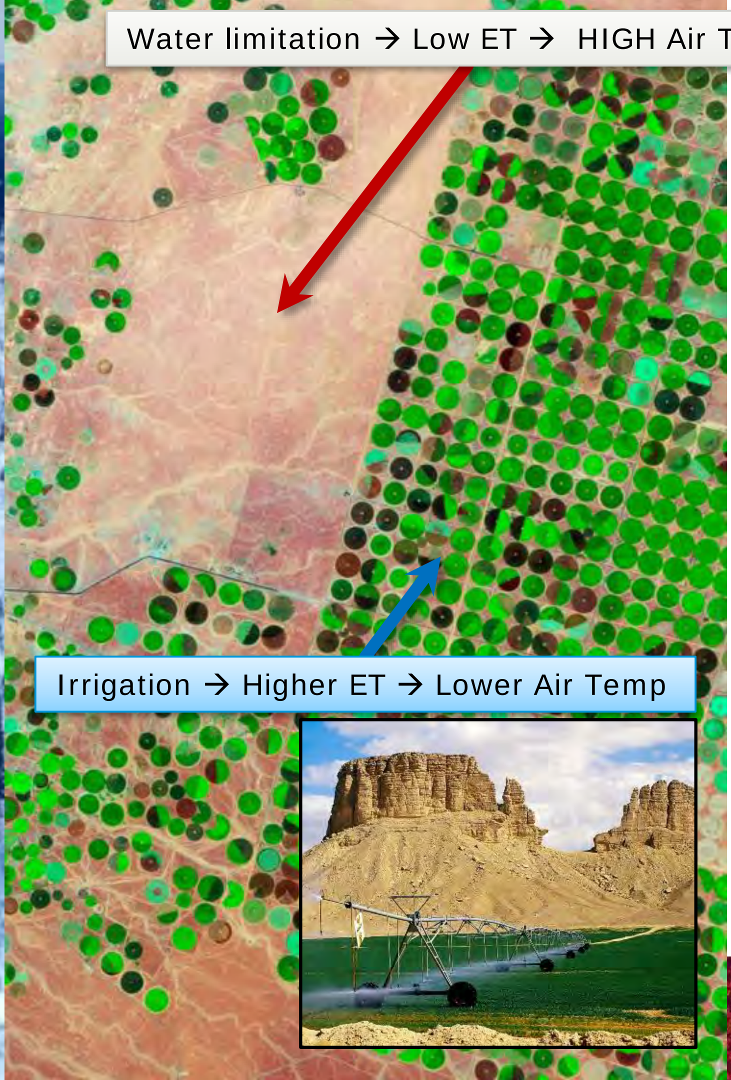
Low albedo → High Absorbed radiation → HIGH Air Temp



High albedo → Low Absorbed radiations → LOW Air Temp

EVAPOTRANSPIRATION

Water limitation → Low ET → HIGH Air Temp



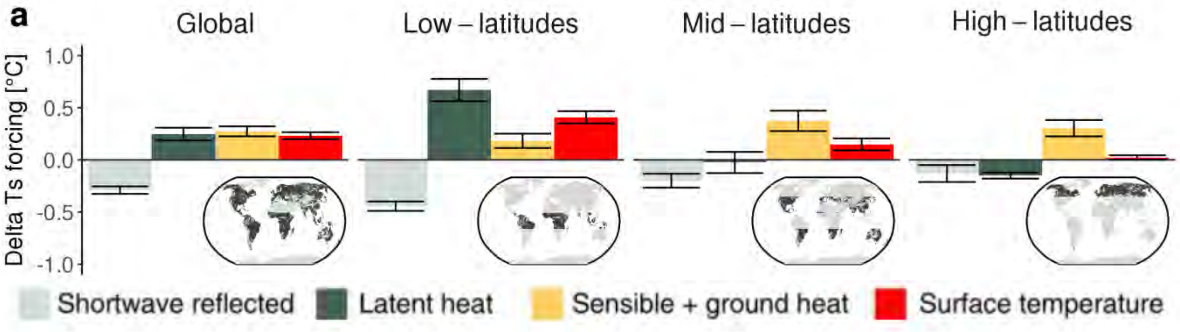
Irrigation → Higher ET → Lower Air Temp

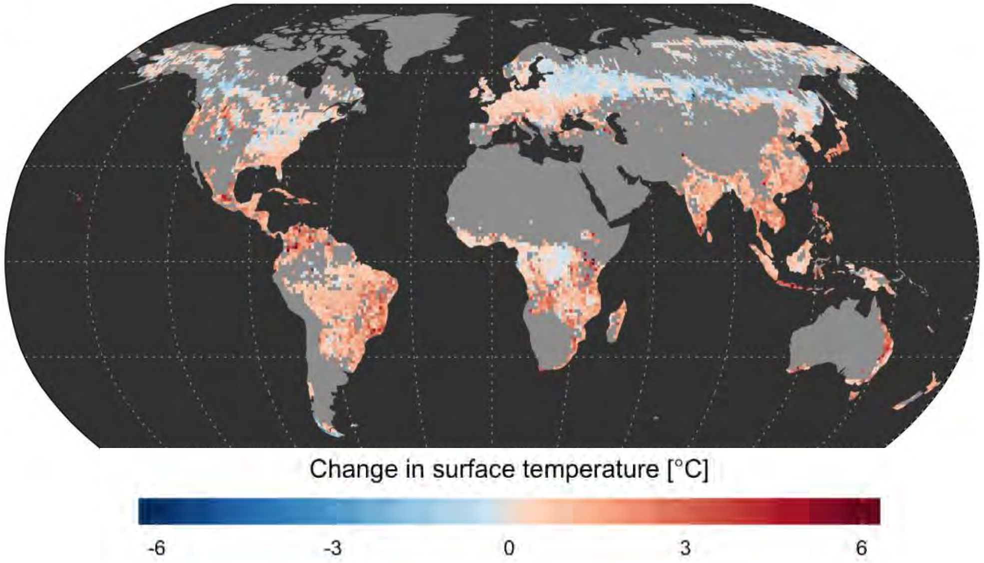
nature COMMUNICATIONS

ARTICLE
DOI: 10.1038/s41467-017-02810-8 OPEN

The mark of vegetation change on Earth's surface energy balance

Gregory Duveiller[1], Josh Hooker[1] & Alessandro Cescatti[1]





Vegetation cover change from 2000 to 2015, dominated by agricultural expansion into tropical forest, has resulting in a local warming of 0.23± 0.03°C.

Duveiller et al. 2018, NCOMM

What would we want to extract from RS?

- Vegetation productivity and biomass
- Energy fluxes (LST, albedo, ET)
- Vegetation type and change

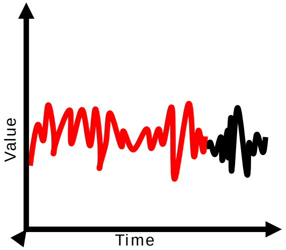
SPACE and TIME

What do we use these estimates for?

- To better understand land surface processes
- To monitor changes in land surface at global to local scales
- To benchmark, calibrate and parametrize land surface models

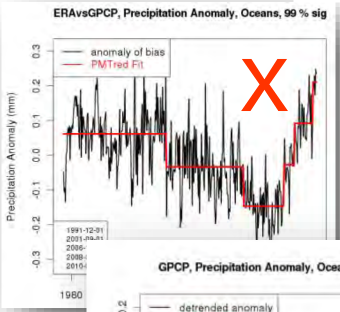
Requirements for climate data

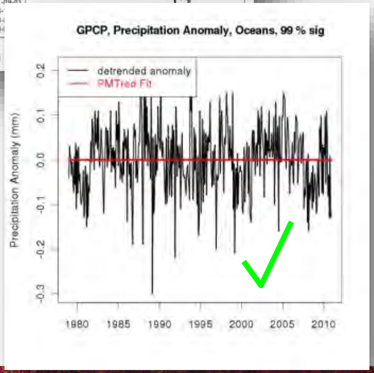
Slide adapted from Jedrzej S. Bojanowsky



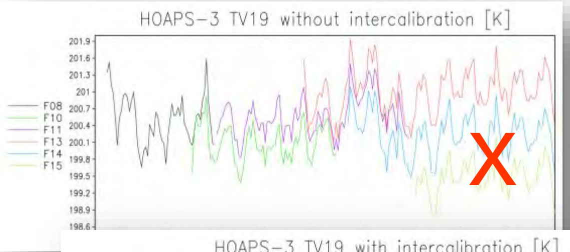
Sufficiently long time series

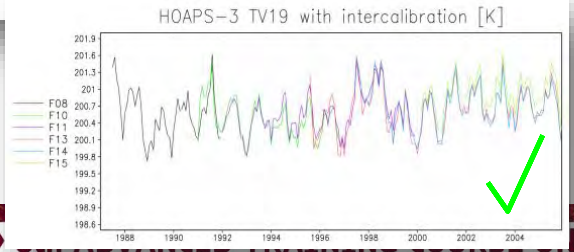
Homogeneous



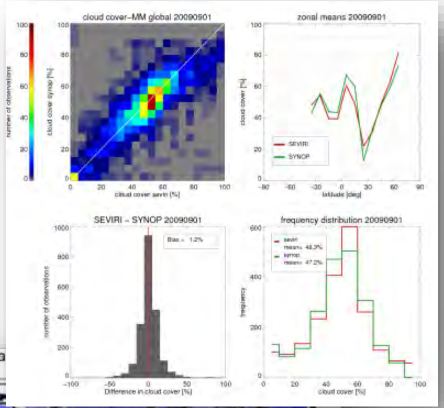


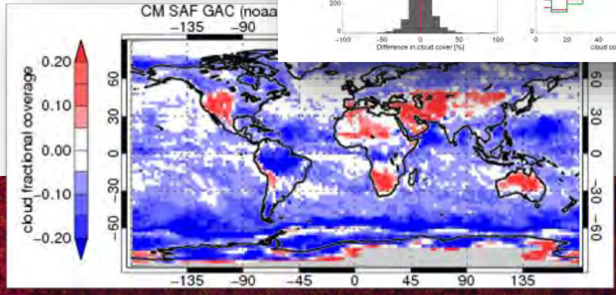
Calibrated





Quality controlled





ESA Climate Change Initiative (CCI)

The Global Climate Observing System (GCOS) developed the concept of the Essential Climate Variable (ECV).

ECVs: Physical, chemical or biological variable (or group of linked variables) that critically contributes to the characterisation of Earth’s climate.

ECVs are defined based on criteria of:

Relevance, *Feasibility* and *Cost effectiveness*

The CCI program is the response of ESA to GCOS.

aerosol cci

biomass cci

cloud cci

cmug cci

fire cci

ghg cci

glaciers cci

antarctic ice sheet cci

ice sheets greenland cci

land cover cci

high resolution land cover cci

land surface temperature cci

ocean colour cci

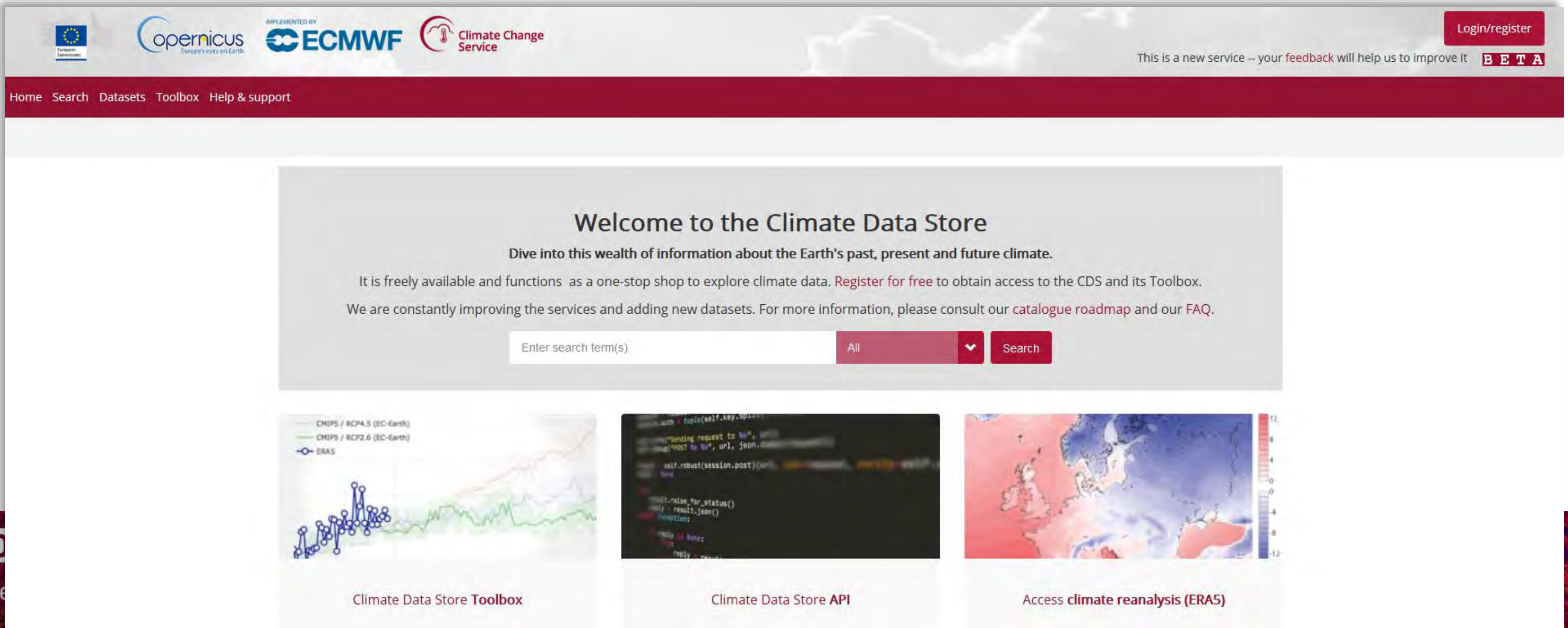
ozone cci

permafrost cci

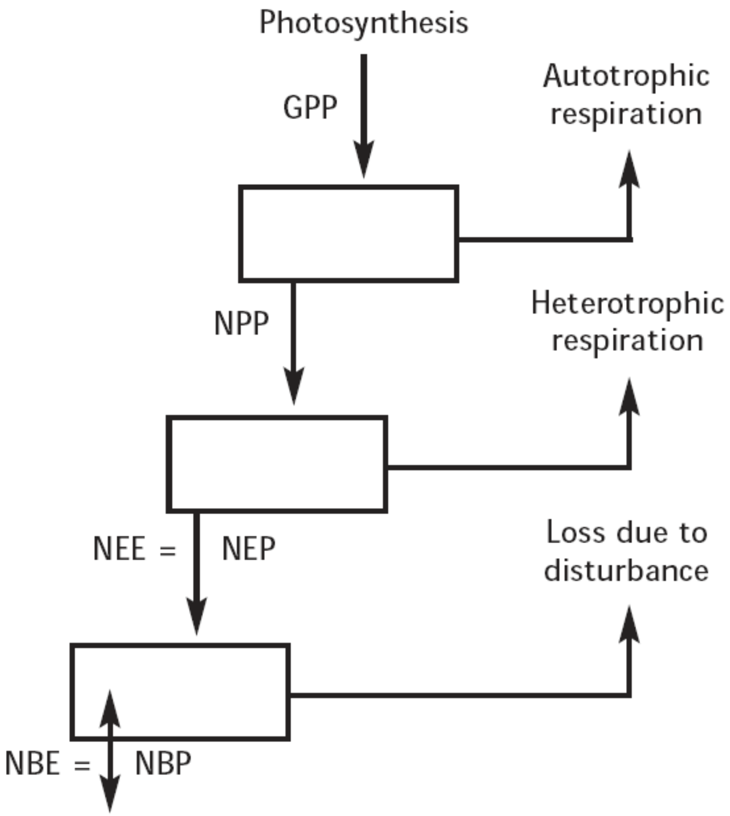
salinity cci

Copernicus is the European Union's Earth Observation Programme, looking at our planet and its environment for the ultimate benefit of all European citizens. It offers information services based on satellite Earth Observation and in situ (non-space) data.

Climate Change Service



Ecological terms commonly used in carbon accounting



GPP [Gross Primary Production]:

total amount of carbon fixed in the process of photosynthesis by plants in an ecosystem

NPP [Net Primary Production]:

net production of organic matter by plants in an ecosystem, that is: GPP - autotrophic respiration

NEP [Net Ecosystem Production]:

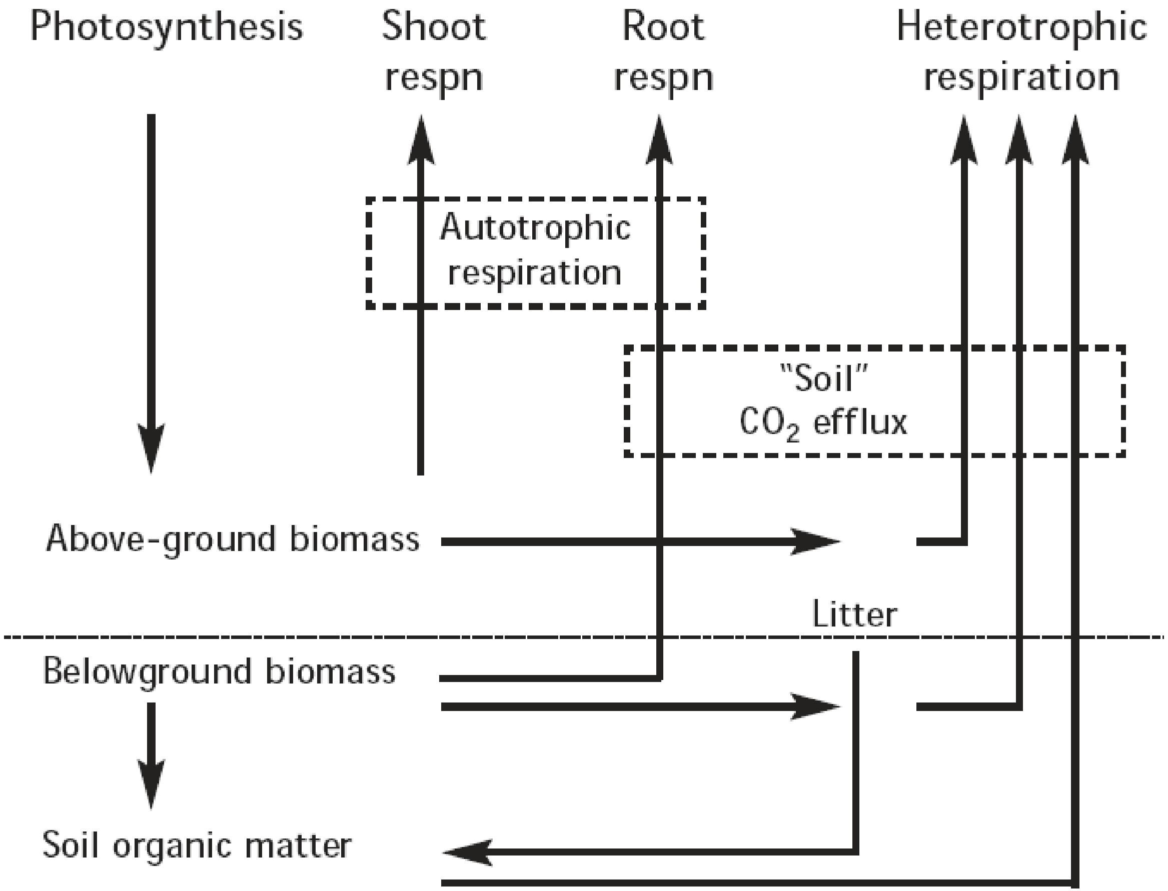
net accumulation of organic matter or carbon by an ecosystem; NEP = NPP − heterotrophic resp.

NBP [Net Biosphere Production]:

net production of organic matter in a region containing a range of ecosystems (a biome) minus what is lost by disturbance (harvest, forest clearance, and fire, etc.)

Kirschbaum, M. U. F., et al. "Definitions of some ecological terms commonly used in carbon accounting." Cooperative Research Centre for Carbon Accounting, Canberra (2001): 2-5.

Complexity of measuring all components…



Kirschbaum, M. U. F., et al. "Definitions of some ecological terms commonly used in carbon accounting." Cooperative Research Centre for Carbon Accounting, Canberra (2001): 2-5.

Productivity measured from flux-towers

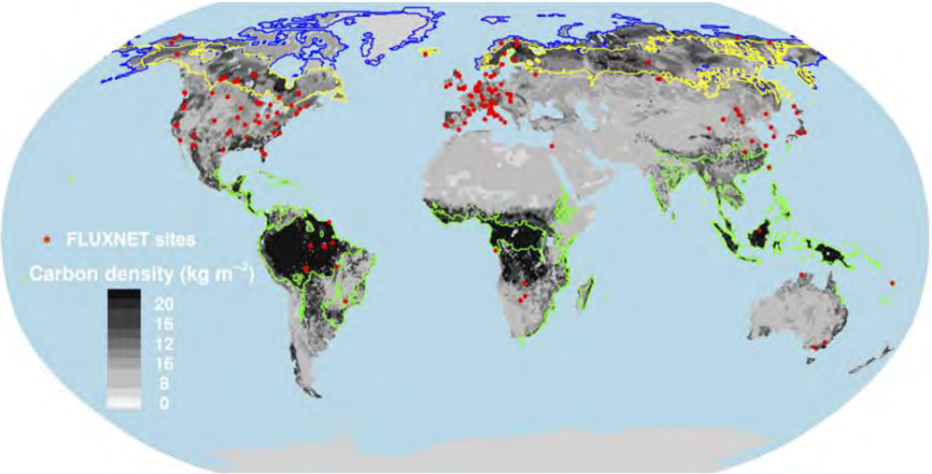
Measures NEE (Net Ecosystem Exchange = NEP)

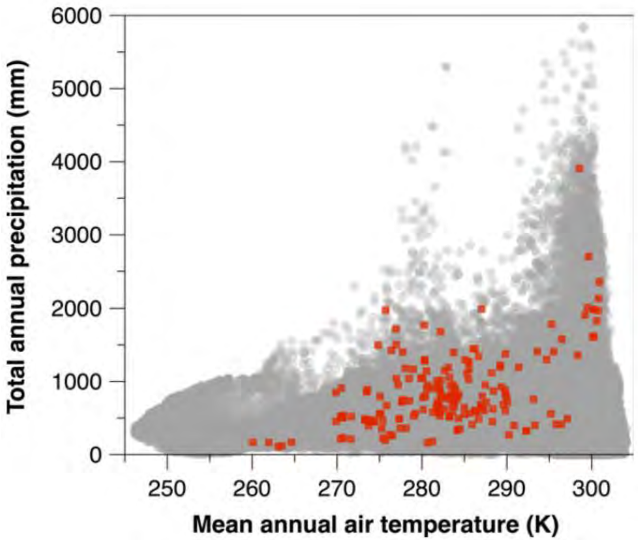
GPP can be derived, but already contains some modelling assumptions to remove respiration

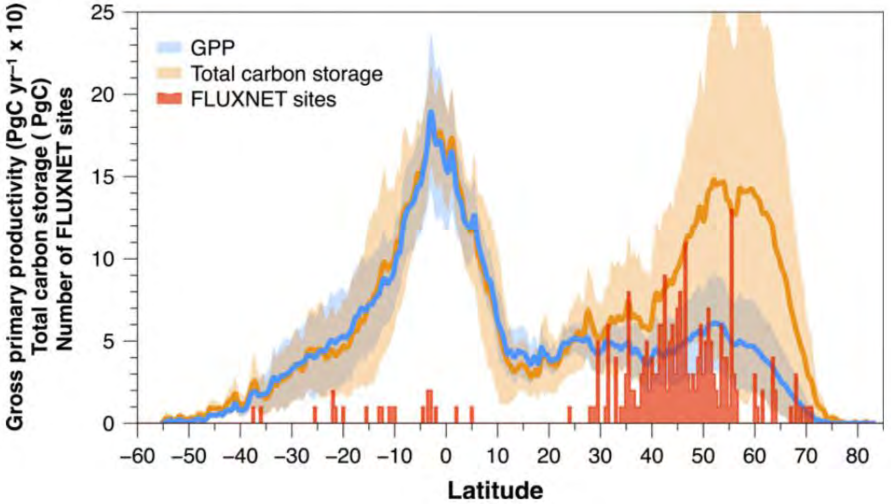
Limited to a very localized area (~1km)

Productivity measured from flux-towers

Sub-optimal spatial distribution despite reasonable climatic distribution

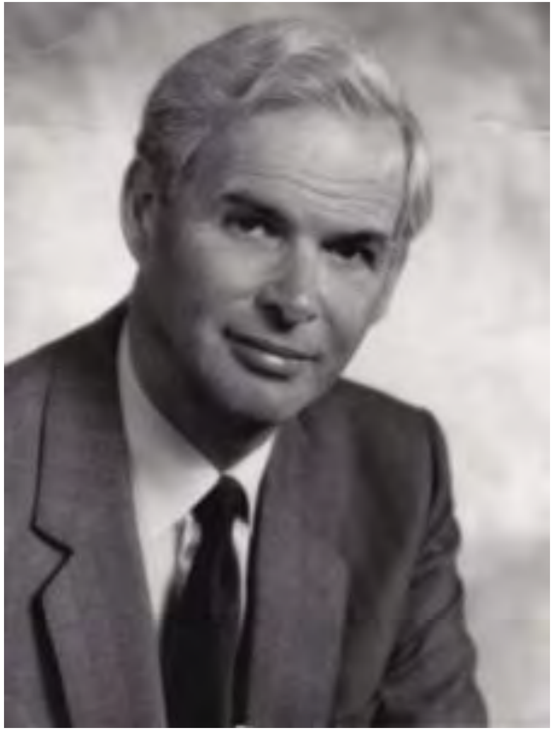






Schimel, D., Pavlick, R., Fisher, J. B., Asner, G. P., Saatchi, S. S., Townsend, P., … Cox, P. (2015). Observing terrestrial ecosystems and the carbon cycle from space. Global Change Biology, 21(5), 1762–76. https://doi.org/10.1111/gcb.12822

Light use efficiency (Monteith approach)



Monteith, J. L. (1972). Solar radiation and productivity in tropical ecosystems. Journal of Applied Ecology, 9(3), 747–766.

Canopy productivity = Radiation interception * Radiation use efficiency

Simple approach that can be linked to remote sensing observations

PAR, APAR and fAPAR

Photosynthetically Active Radiation (PAR):

Radiation between 400 and 700 nm that photosynthetic organisms are able to use in the process of photosynthesis.

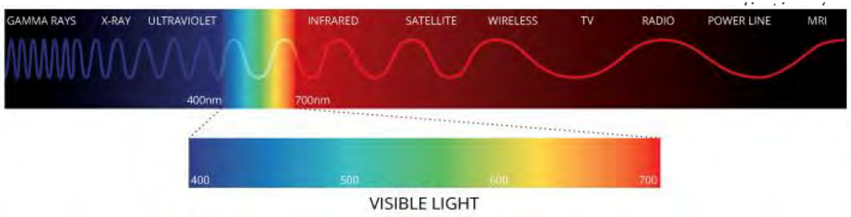
Coincides with visible light [Units: µmol photons m−2 s−1]

Absorbed PAR (APAR):

Quantity of PAR absorbed by the plants

Often considered equal to
intercepted PAR

Source: http://www.fondriest.com/environmental-measurements/parameters/weather/photosynthetically-active-



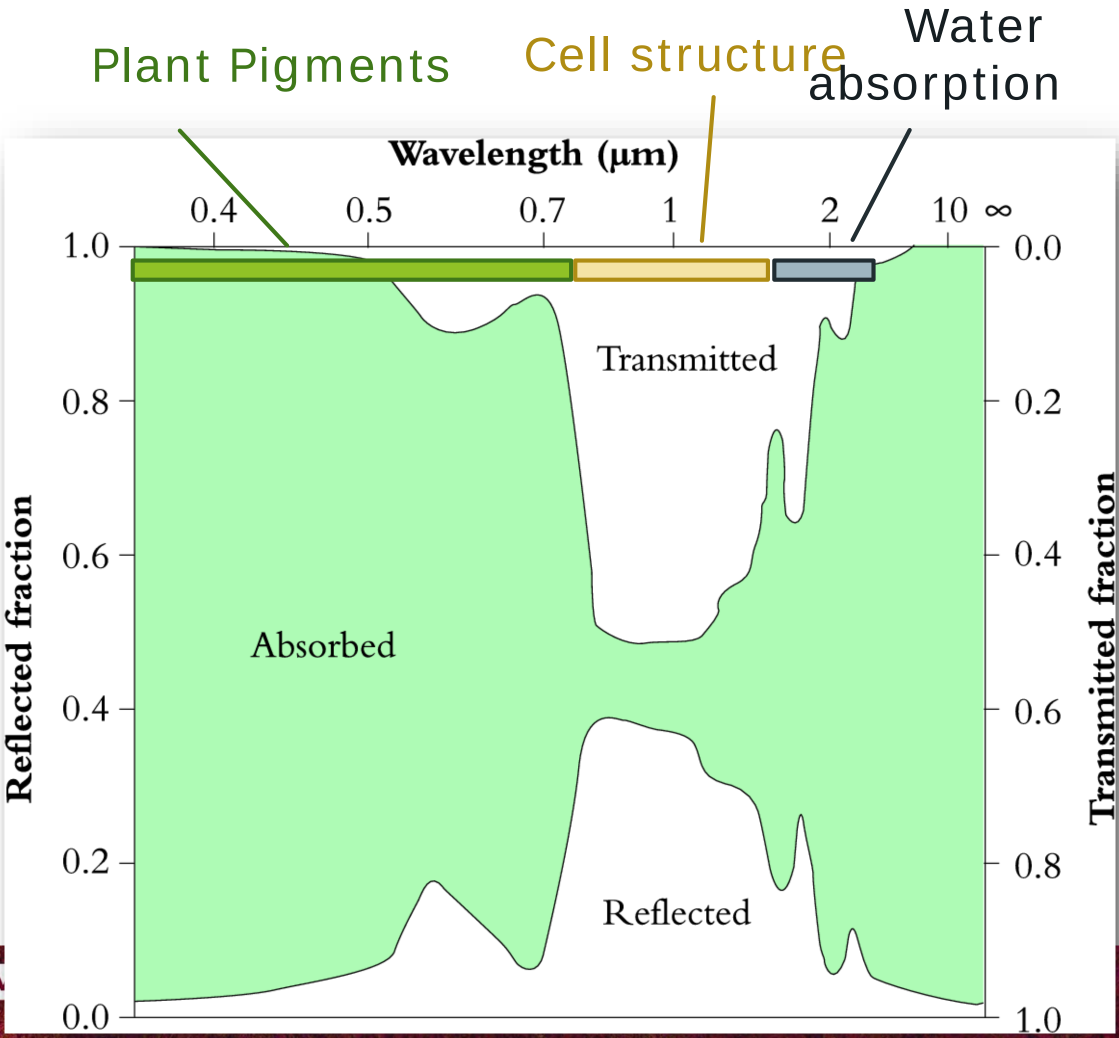
Fraction of APAR (fAPAR):

Normalized variable between 0 and 1

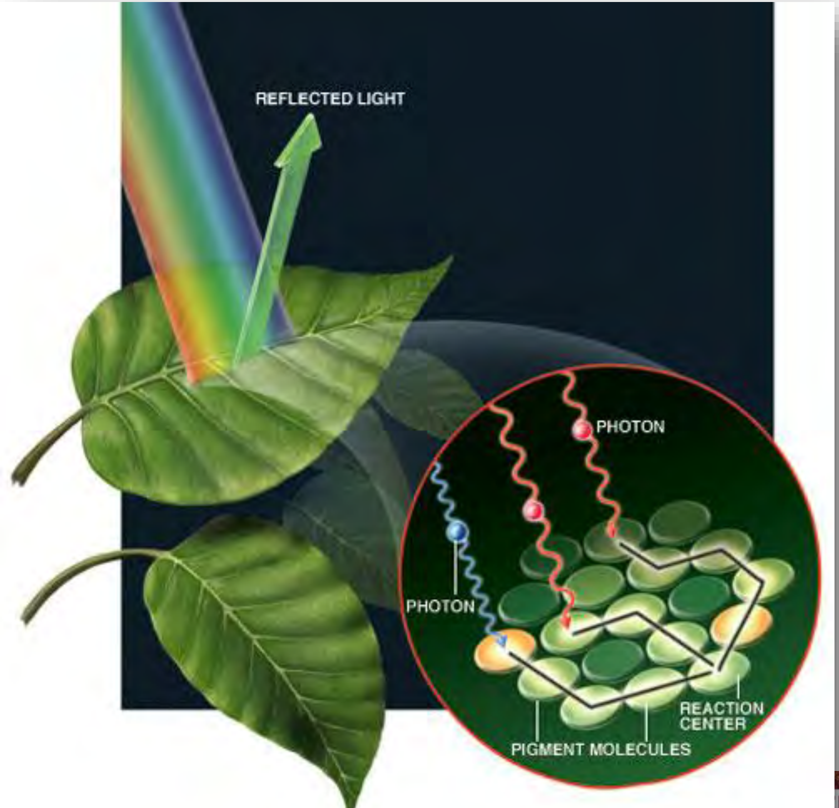
fAPAR = APAR/PAR

Spectral properties of vegetation

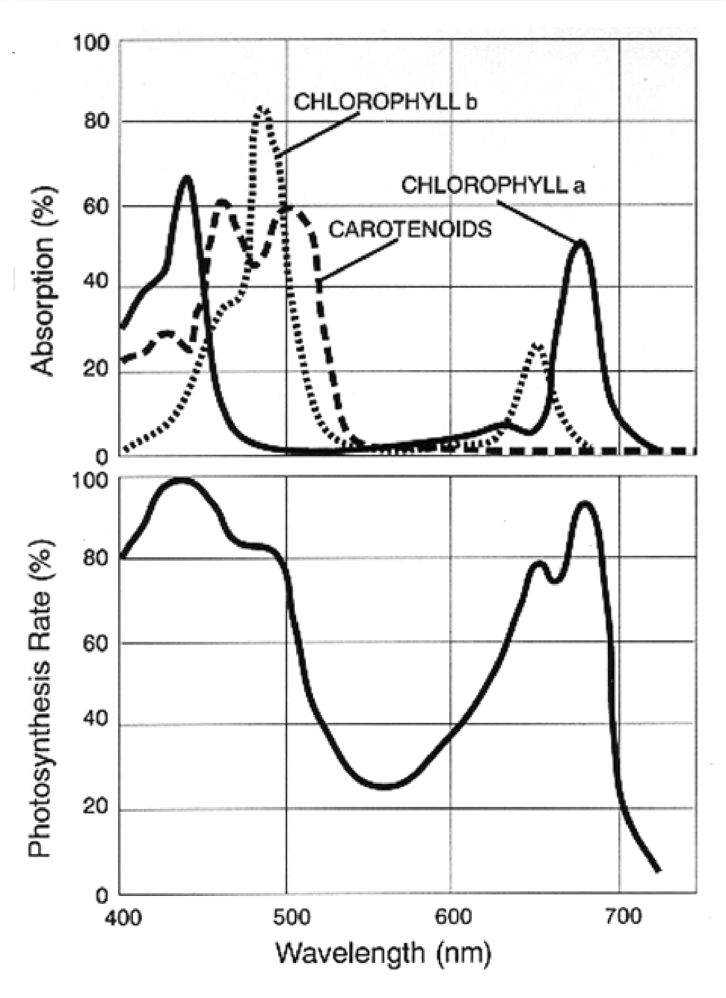
Source: *Plants in Action, published by the Australian Society of Plant Scientists, http://plantsinaction.science.uq.edu.au/edition1/*



Plant pigments

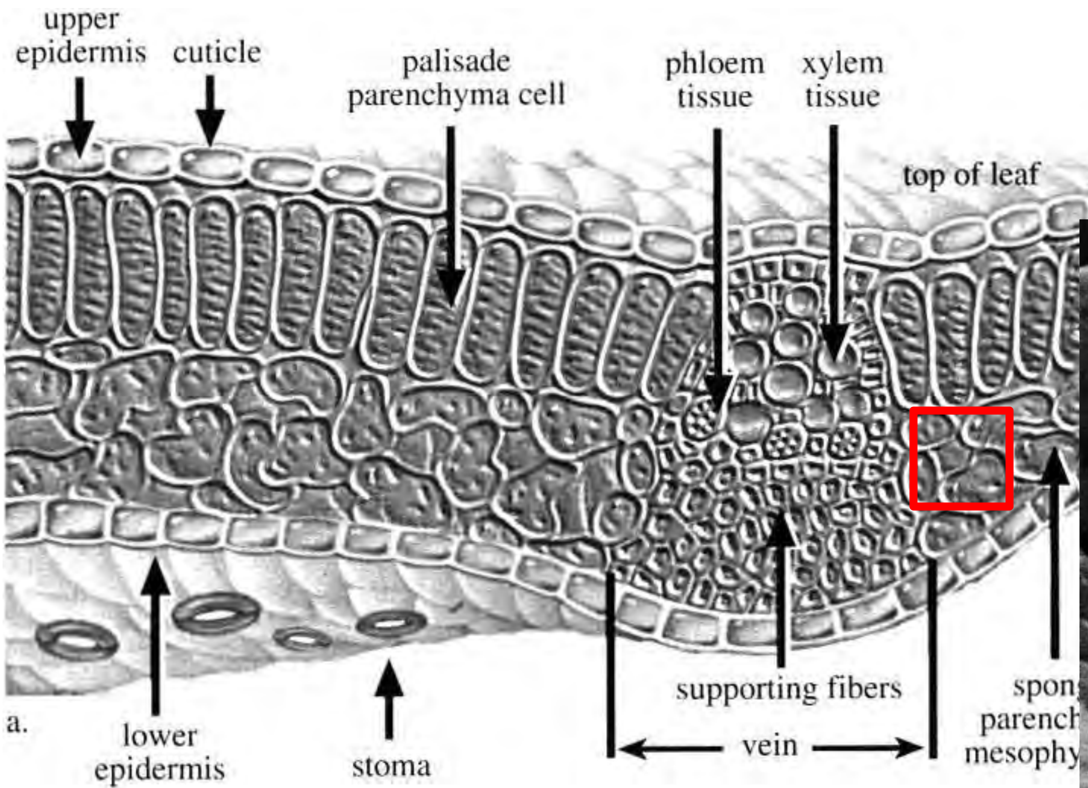


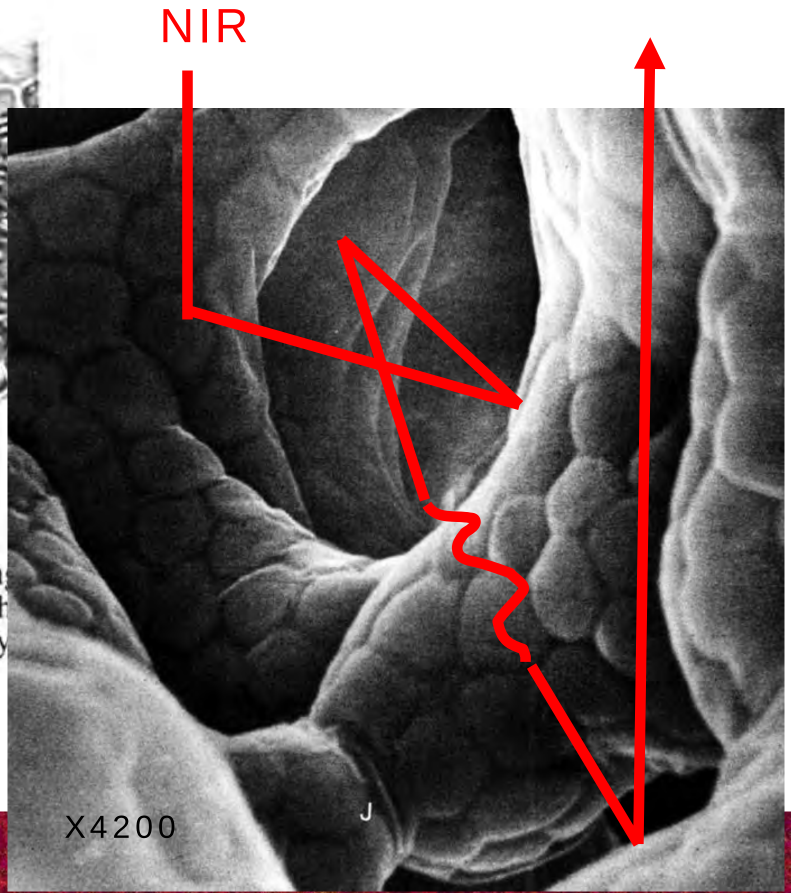
Source: Scientific American



Source: http://www.life.uiuc.edu/govindjee/paper/gov.html, from "Concepts in Photobiology: Photosynthesis and Photomorphogenesis", Edited by GS Singhal, G Renger, SK Sopory, K-D Irrgang

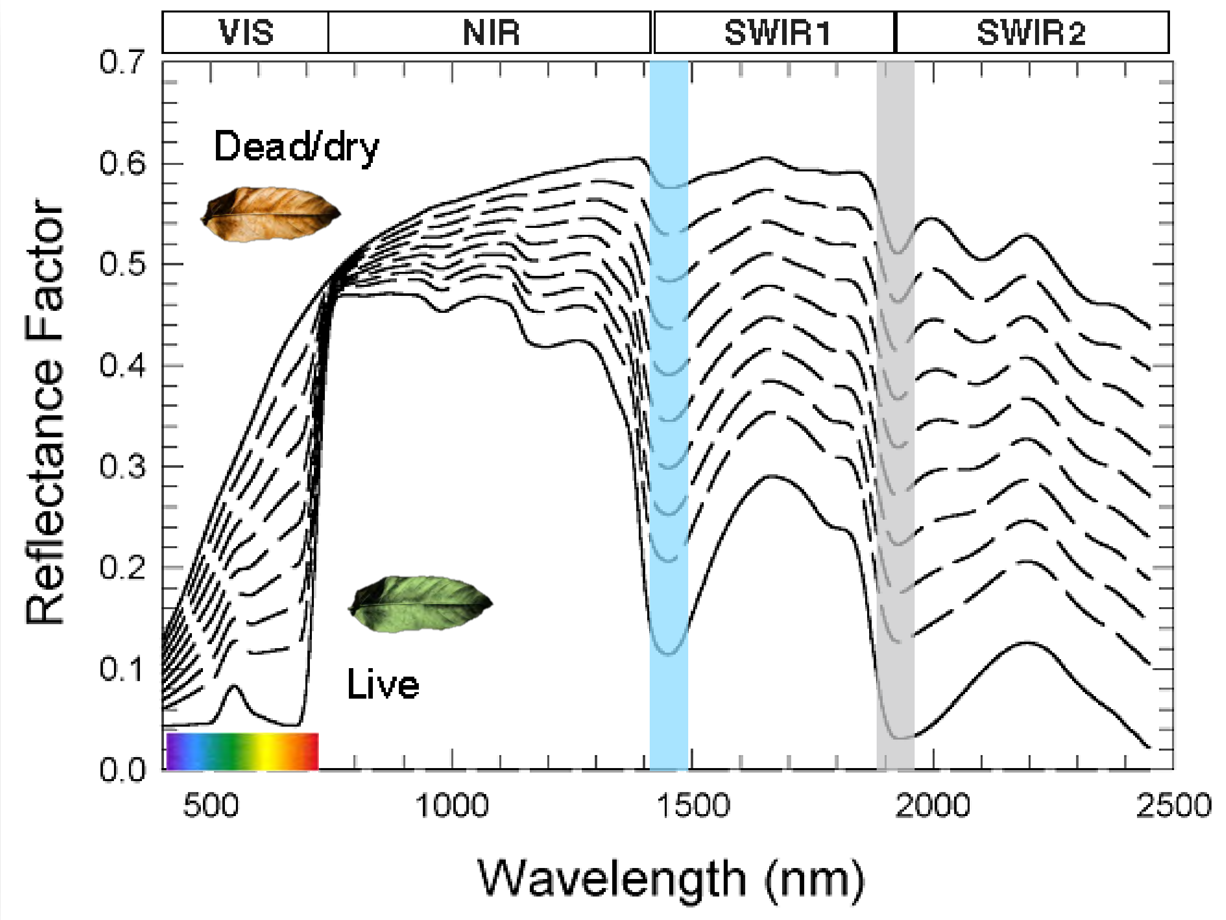
Cell Structure





Cell structure strongly scatters NIR radiation to prevent cell damage

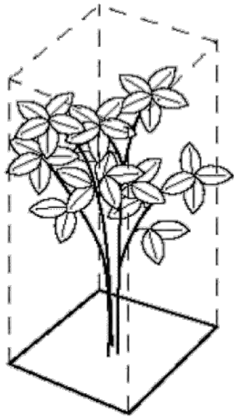
Absorption from water in the plants



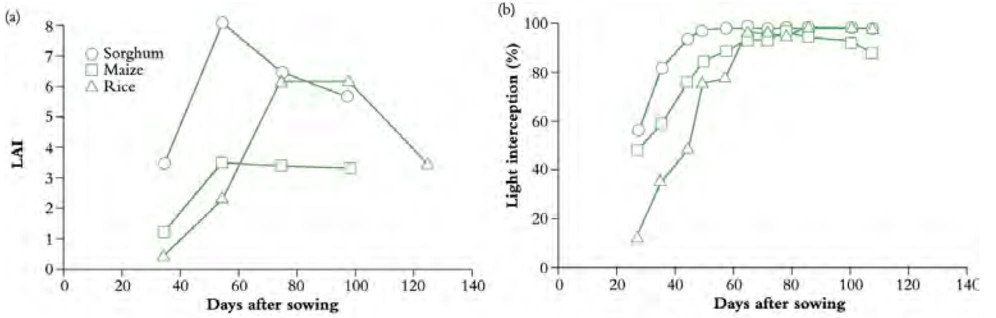
Source: http://www.exelisvis.com/docs/NonPhotosyntheticVegetation.html [incorrectly cited as coming from: Asner, G.P., 1998. RSE.]

Source: *Plants in Action, published by the Australian Society of Plant Scientists, http://plantsinaction.science.uq.edu.au/edition1/*

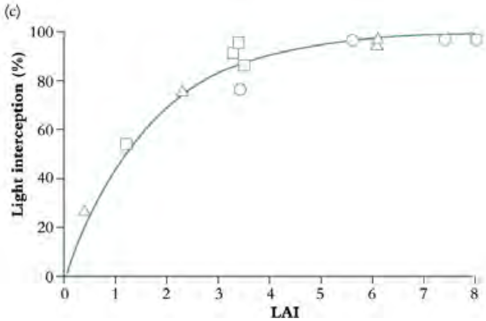
Leaf Area Index (LAI)

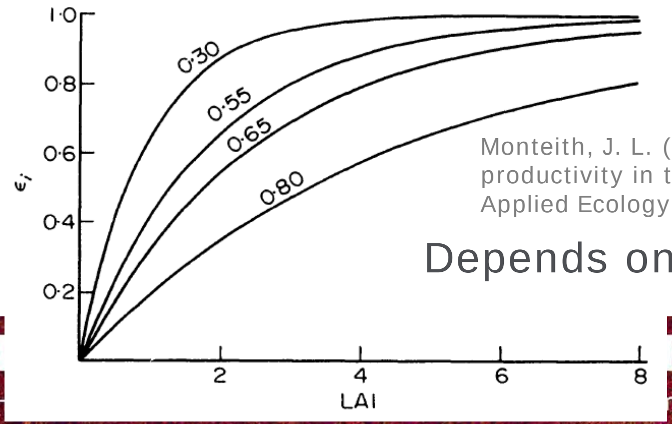


Defined as half the total developed area of green leaves per unit of ground horizontal surface area [units: m2 m-2]



Interface between atmosphere and vegetation.





Monteith, J. L. (1972). Solar radiation and productivity in tropical ecosystems. Journal of Applied Ecology, 9(3), 747–766.

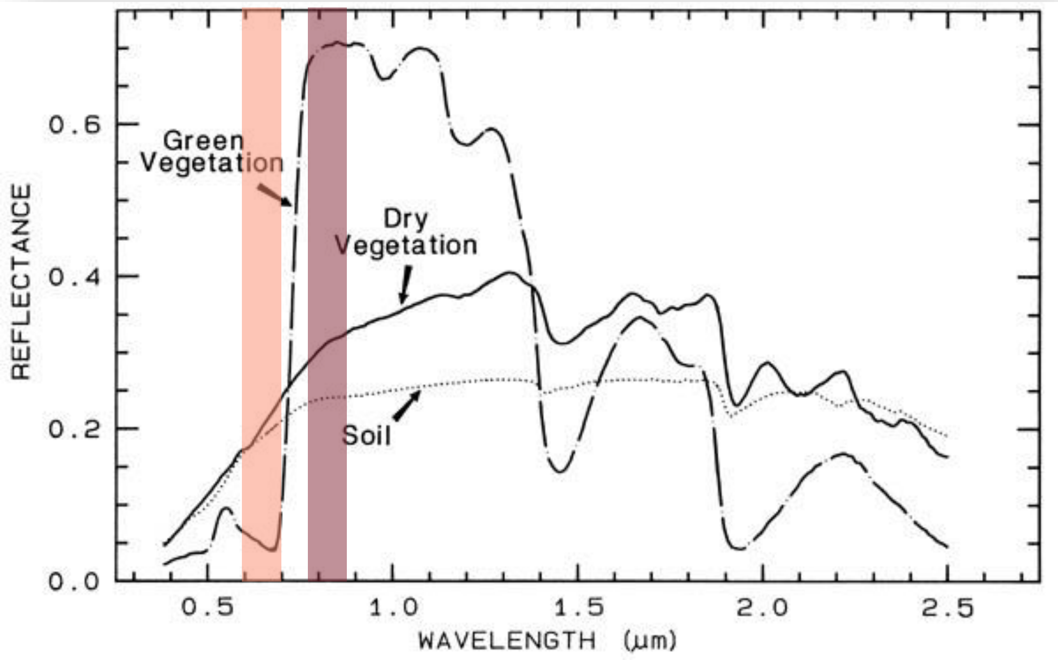
Depends on leaf geometry

Useful to describe light interception: $I = I_0 e^{-kLAI}$

Measuring 'greenness'

Normalized Difference Vegetation Index

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$



Exploits particular spectral properties of vegetation

Partly independent of viewing geometry

Proposed by Rouse et al. 1974

Popularized by Tucker since 1980

Vegetation indices

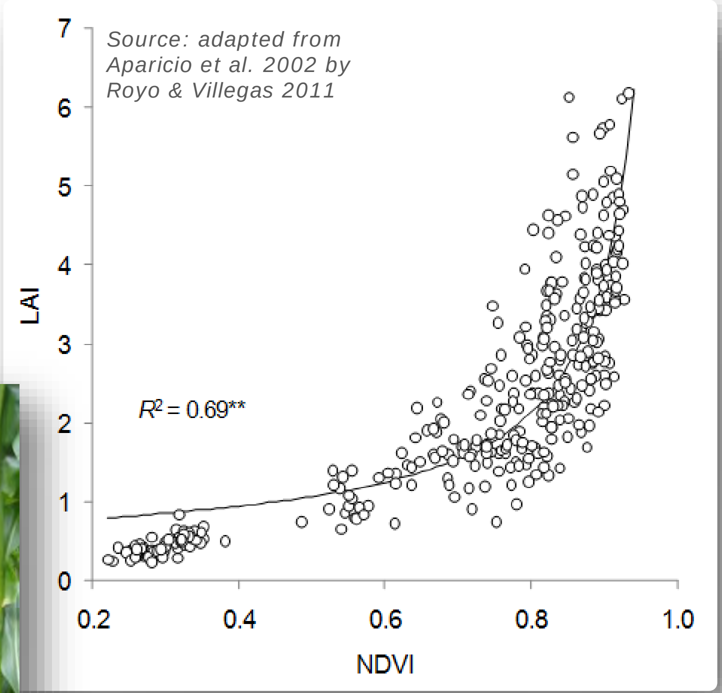
- Convenient way to resume information
- Exploit the particular spectral properties of vegetation
- Depend on spectral response of the sensors (which changes even for bands with same names)
- Potentially unlimited number of combinations

Differenced Vegetation Index	DVI	$(2.4\text{MSS7} - \text{MSS5})$	Richardson and Wiegand, 1977
Misra Soil Brightness Index	MSBI	$(0.406\text{MSS4} + 0.600\text{MSS5} + 0.645\text{MSS6} + 0.243\text{MSS7})$	Misra et al., 1977
Misra Green Vegetation Index	MGVI	$(-0.386\text{MSS4} - 0.530\text{MSS5} + 0.535\text{MSS6} + 0.532\text{MSS7})$	Misra et al., 1977
Misra Yellow Vegetation Index	MYVI	$(0.723\text{MSS4} - 0.597\text{MSS5} + 0.206\text{MSS6} - 0.278\text{MSS7})$	Misra et al., 1977
Misra Non Such Index	MNSI	$(0.404\text{MSS4} - 0.039\text{MSS5} - 0.505\text{MSS6} + 0.762\text{MSS7})$	Misra et al., 1977
Perpendicular Vegetation Index	PVI	$\sqrt{(\rho_{\text{sol}} - \rho_{\text{végé}})^2_R + (\rho_{\text{sol}} - \rho_{\text{végé}})^2_{\text{NIR}}}$	Richardson and Wiegand, 1977
Ashburn Vegetation Index	AVI	$(2.0\text{MSS7} - \text{MSS5})$	Ashburn, 1978
Greenness Above Bare Soil	GRABS	$(\text{GVI} - 0.09178\text{SBI} + 5.58959)$	Hay et al., 1979
Multi-Temporal Vegetation Index	MTVI	$(\text{NDVI(date 2)} - \text{NDVI(date 1)})$	Yazdani et al., 1981
Greenness Vegetation and Soil Brightness	GVSB	$\frac{\text{GVI}}{\text{SBI}}$	Badhwar, 1981
Adjusted Soil Brightness Index	ASBI	$(2.0\ \text{YVI})$	Jackson et al., 1983
Adjusted Green Vegetation Index	AGVI	$\text{GVI} - (1 + 0.018\text{GVI})\text{YVI} - \text{NSI}/2$	Jackson et al., 1983
Transformed Vegetation Index	TVI	$\frac{(\text{NDVI} + 0.5)}{\lvert\text{NDVI} + 0.5\rvert}\sqrt{\lvert\text{NDVI} + 0.5\rvert}$	Perry and Lautenschlager, 1984
Differenced Vegetation Index	DVI	$(\text{NIR} - \text{R})$	Clevers, 1986
Normalized Difference Greenness Index	NDGI	$\frac{(\text{G} - \text{R})}{(\text{G} + \text{R})}$	Chamard et al., 1991
Redness Index	RI	$\frac{(\text{R} - \text{G})}{(\text{R} + \text{G})}$	Escadafal and Huete, 1991
Normalized Difference Vegetation Index	NDVI	$\frac{(\text{NIR} - \text{R})}{(\text{NIR} + \text{R})}$	Rouse et al., 1974
Perpendicular Vegetation Index	PVI	$\frac{(\text{NIR} - aR - b)}{\sqrt{a^2 + 1}}$	Jackson et al., 1980
Soil Adjusted Vegetation Index	SAVI	$\frac{(\text{NIR} - \text{R})}{(\text{NIR} + \text{R} + \text{L})}(1 + \text{L})$	Huete, 1988
Transformed SAVI	TSAVI	$\frac{[a(\text{NIR} - aR - b)]}{(R + a\text{NIR} - ab)}$	Baret et al., 1989
Transformed SAVI	TSAVI	$\frac{[a(\text{NIR} - aR - b)]}{[R + a\text{NIR} - ab + X(1 + a^2)]}$	Baret and Guyot, 1991
Atmospherically Resistant Vegetation Index	ARVI	$\frac{(\text{NIR} - \text{RB})}{(\text{NIR} + \text{RB})}$ $\text{RB} = \text{R} - \gamma(\text{B} - \text{R})$	Kaufman and Tanré, 1992
Global Environment Monitoring Index	GEMI	$\text{GEMI} = \eta(1 - 0.25\eta) - \frac{(\text{R} - 0.125)}{(1 - \text{R})}$ $\eta = \frac{[2(\text{NIR}^2 - \text{R}^2) + 1.5\text{NIR} + 0.5\text{R}]}{(\text{NIR} + \text{R} + 0.5)}$	Pinty and Verstraete, 1992
Transformed Soil Atmospherically Resistant Vegetation Index	TSARVI	$\frac{[a_{rb}(\text{NIR} - a_{rb}\text{RB} - b_{rb})]}{[\text{RB} + a_{rb}\text{NIR} - a_{rb}b_{rb} + X(1 + a^2_{rb})]}$	Bannari et al., 1994
Modified SAVI	MSAVI	$\frac{2\text{NIR} + 1 - \sqrt{(2\text{NIR} + 1)^2 - 8(\text{NIR} - \text{R})}}{2}$	Qi et al., 1994
Angular Vegetation Index	AVI	$\tan^{-1}\left\{\frac{\lambda_3 - \lambda_2}{\lambda_2}[\text{NIR} - \text{R}]^{-1}\right\} + \tan^{-1}\left\{\frac{\lambda_2 - \lambda_1}{\lambda_2}[\text{G} - \text{R}]^{-1}\right\}$	Plummer et al., 1994

Retrieving biophysical variables (fAPAR, LAI) from RS

Empirical methods

- Establishment of a statistical relationship between VI or ρ and field measured biophysical variables
- Require intensive field measurements for calibration and validation
- Relation is typically limited to large geographic extent (for now)



Drones, Big Data and machine learning should revolutionize field data collections in the near-future

Retrieving biophysical variables (fAPAR, LAI) from RS

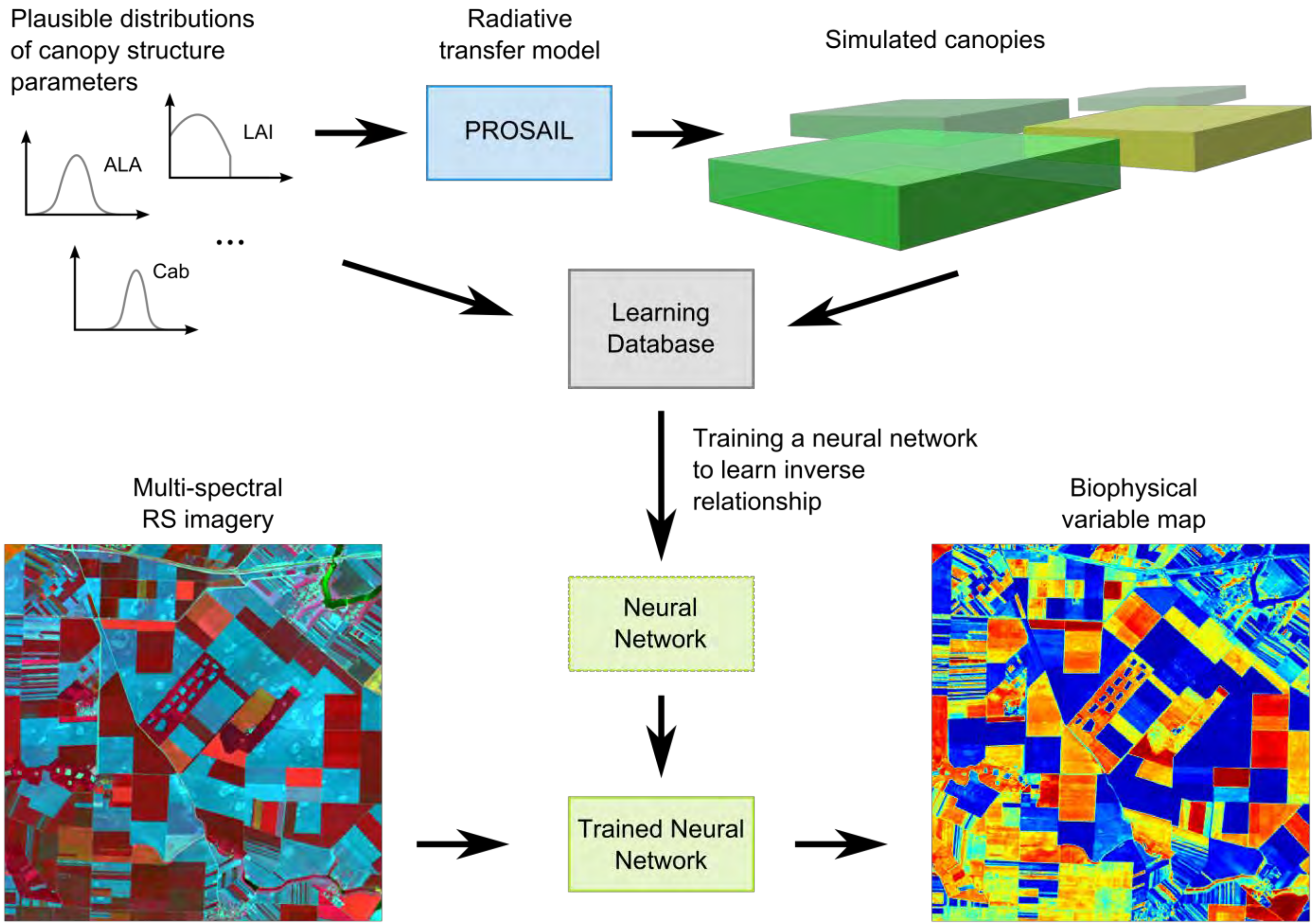
Physical methods

- Replacement of field measurements by radiative transfer models (RTMs)

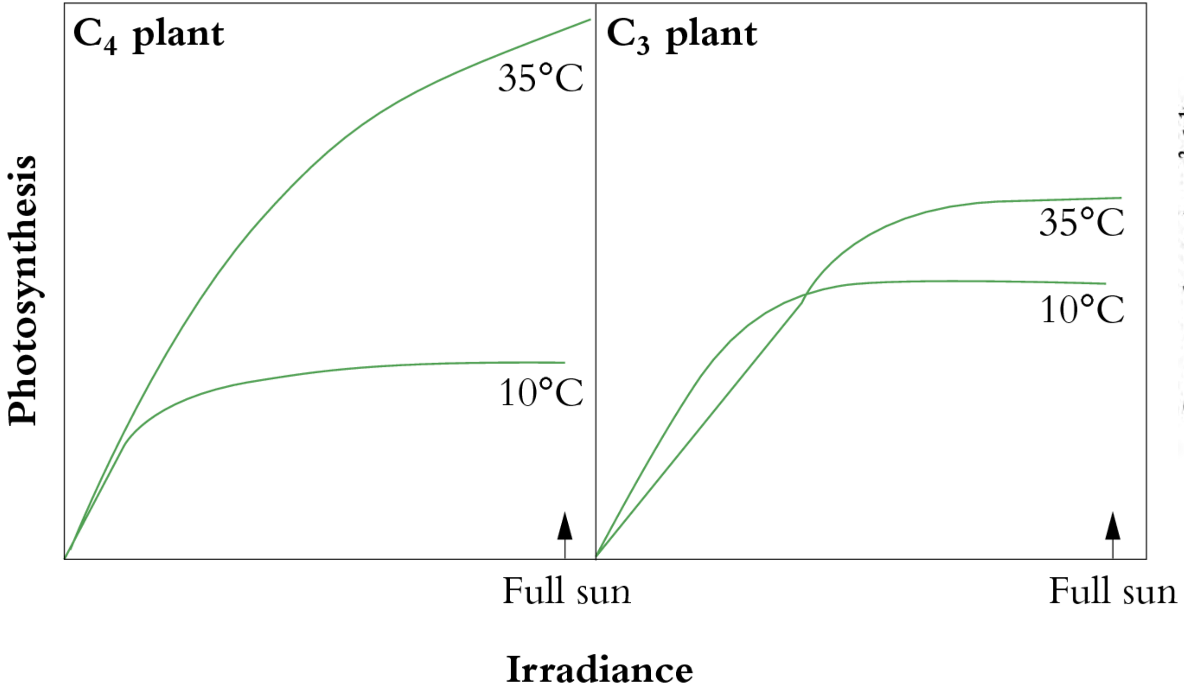
Source: http://fapar.jrc.ec.europa.eu/WWW/Data/Pages/FAPAR_Software/Images/semi-discrete.gif

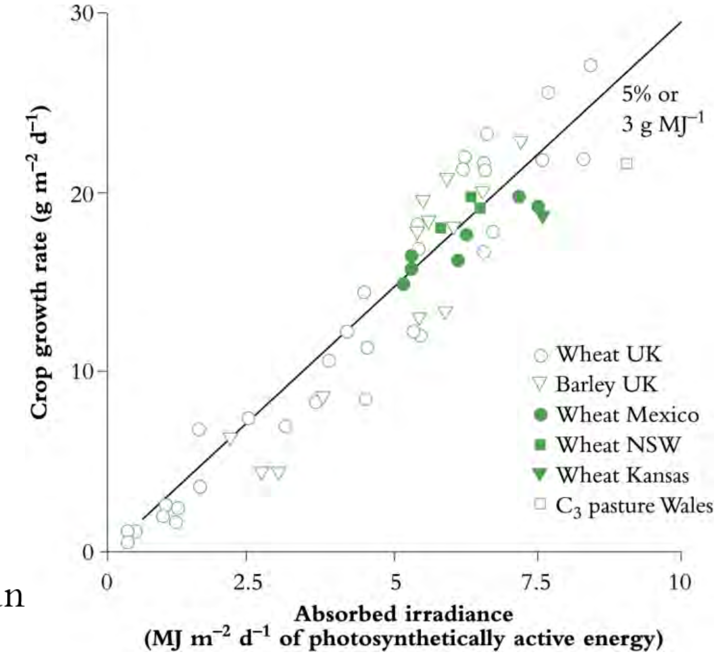
- Mathematical inversion necessary, but difficult because it is an ill-posed problem
- Method is transportable across landscapes as long as RTM is valid

Hybrid method with neural network inversion of RTM

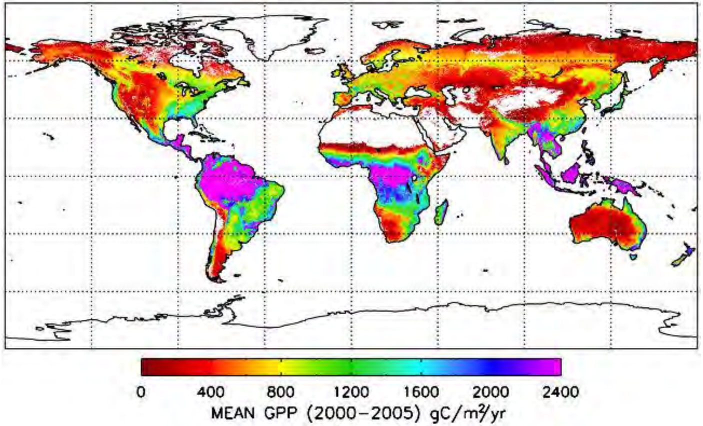


Light use efficiency





Source: Plants in Action, published by the Australian Society of Plant Scientists, http://plantsinaction.science.uq.edu.au/edition1/



Source: *http://www.ntsg.umt.edu/project/modis/mod17.php*

MODIS GPP/NPP Project (MOD17)

Land cover/ biome maps

Set for different vegetation types and climatic conditions

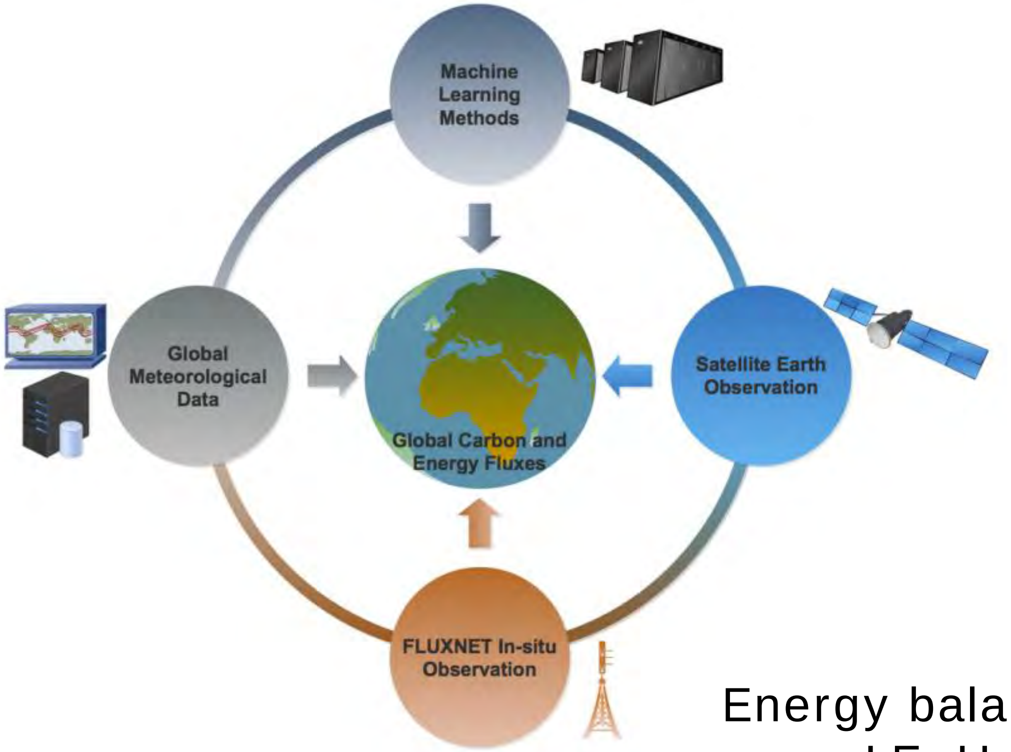
Meteorology

*PAR * fAPAR*

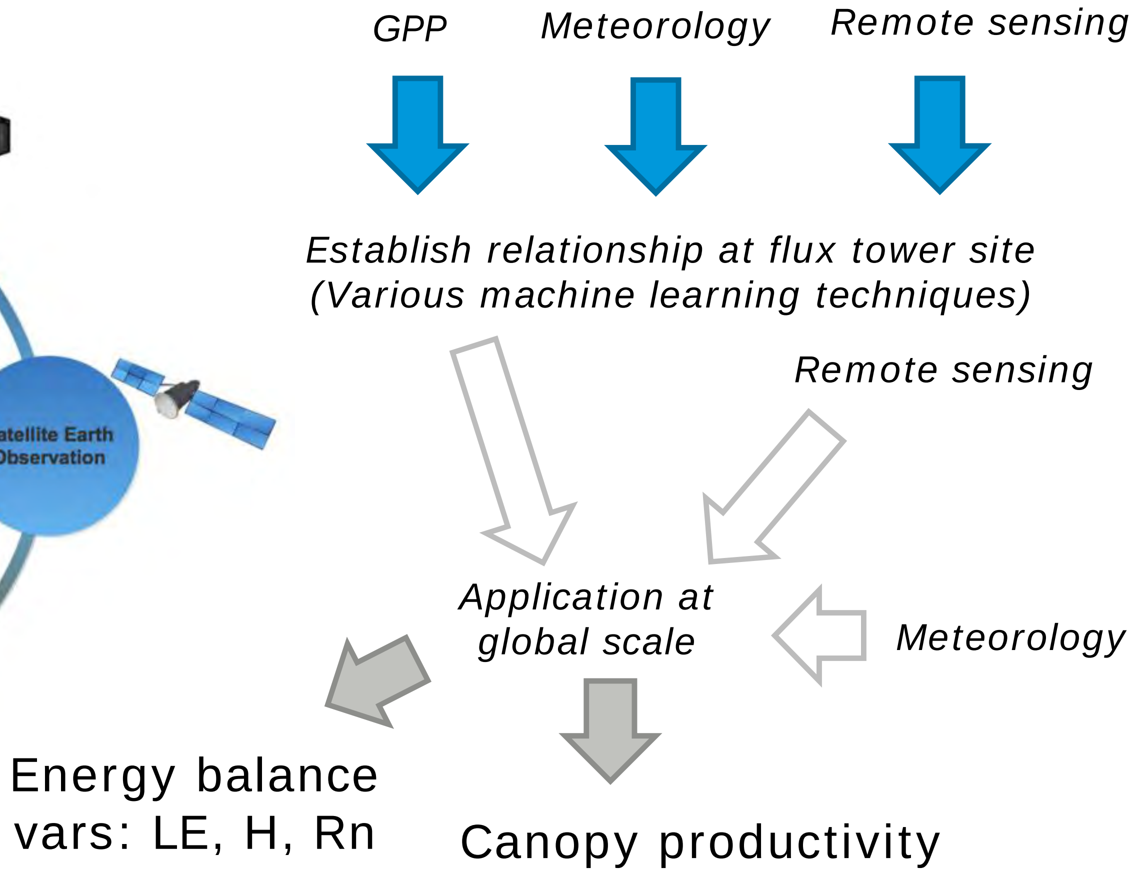
Down-regulated if water-stressed and/or cold temperature condition

Canopy productivity = Radiation interception * Radiation use efficiency

FLUXCOM

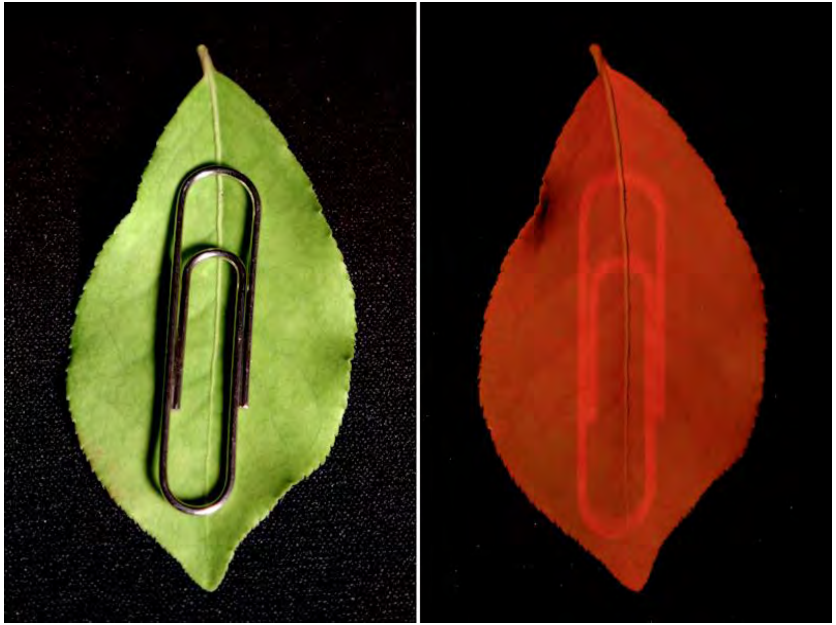


Source: http://www.fluxcom.org/



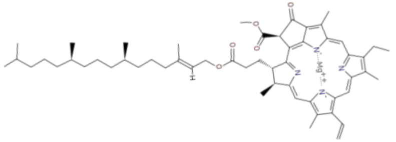
Exploring other avenues …

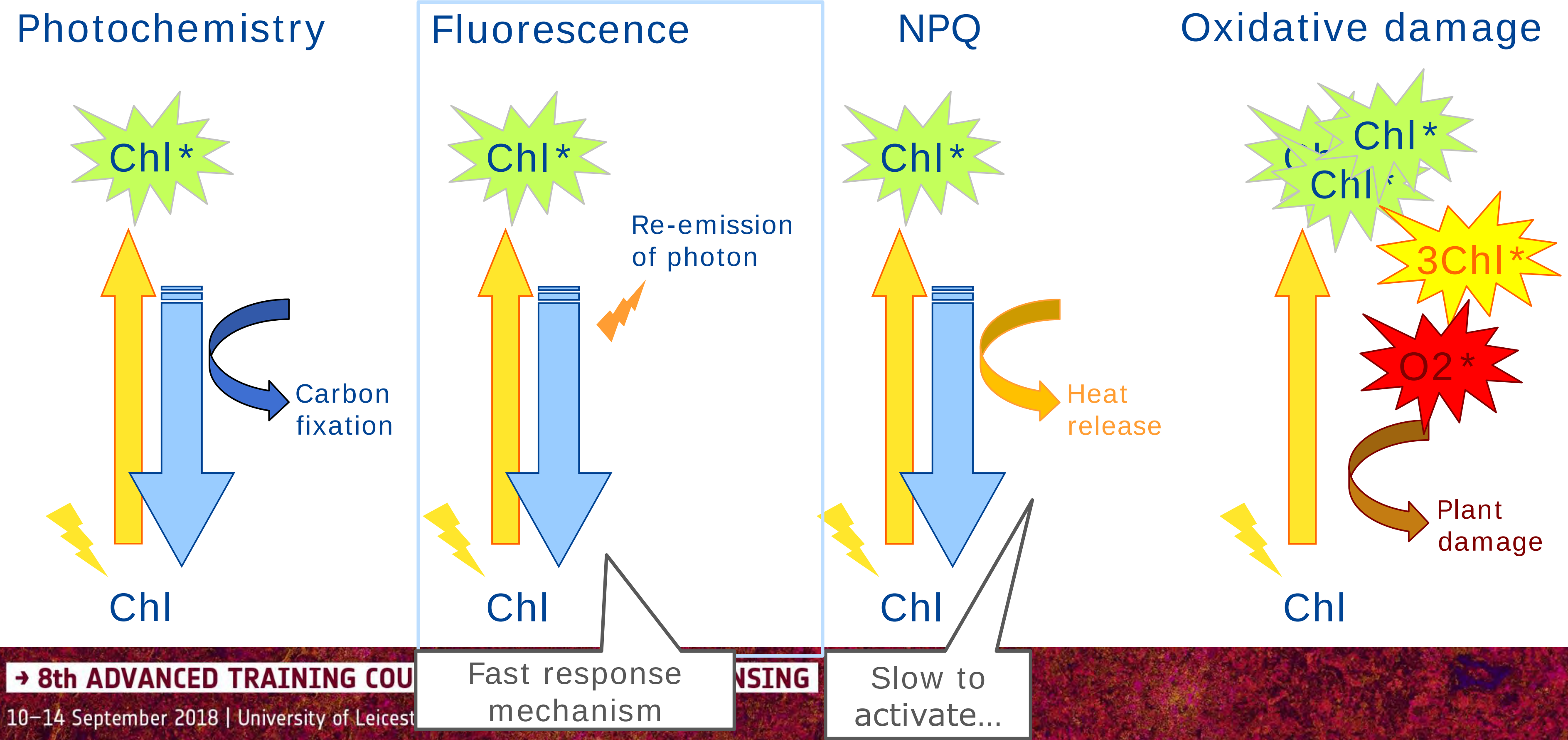
- (Sun-induced) chlorophyll fluorescence (SIF) emitted by the photosynthetic machinery
- Responds instantaneously to perturbations in the environmental conditions such as light and water stress
- This allows to translate effects of stress which do not necessarily cause a reduction of Chl or LAI
- Can provide early and direct diagnostic of functional status of vegetation… proxy for photosynthetic activity



http://www.nightsea.com/articles/fluorescence-photography-illuminates-chlorophyll/

The various fates of exited chlorophyll…

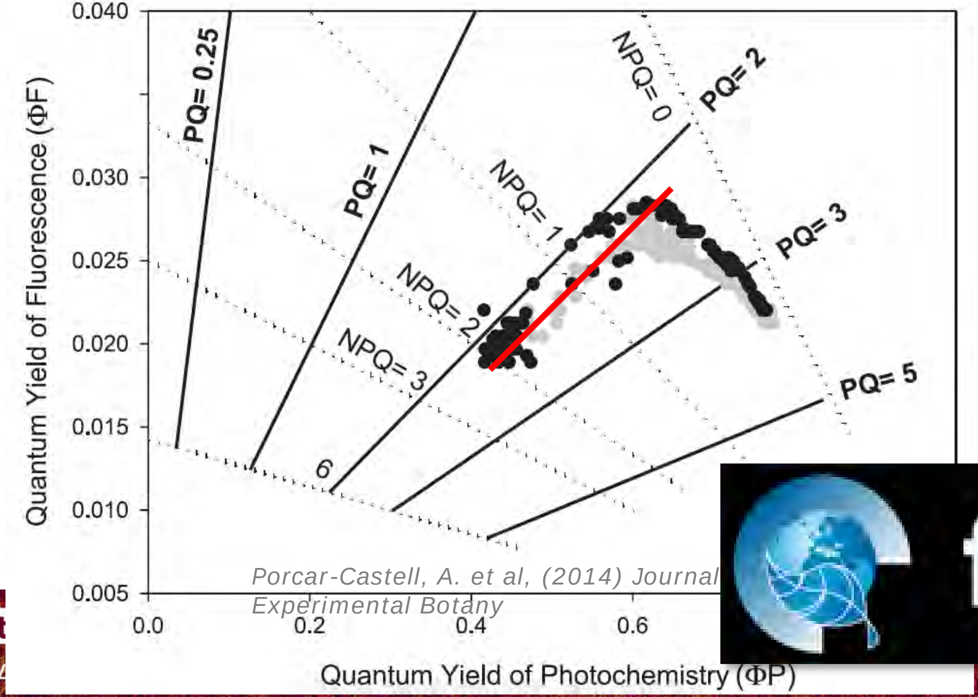




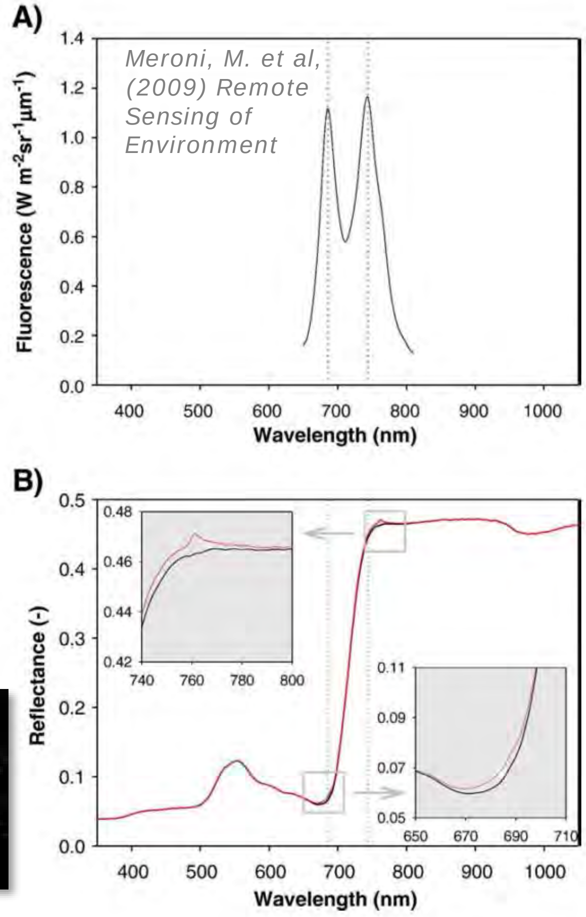
The challenge of retrieving SIF from satellite RS

Only 1-5% of the reflected signal !!!

Fluorescence is proportional to photosynthesis only in some conditions



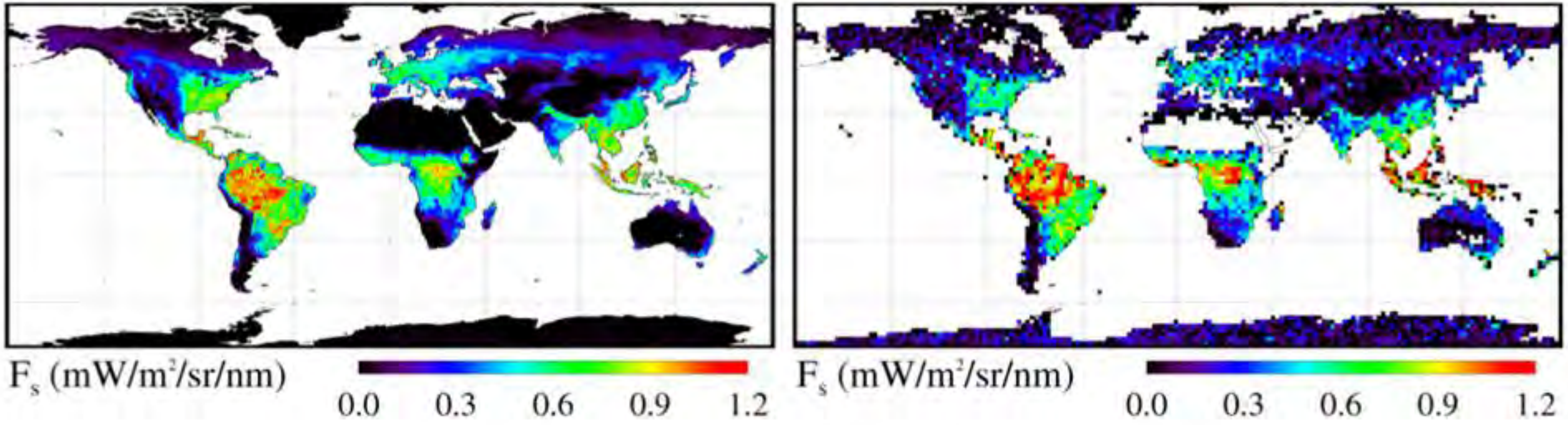
Porcar-Castell, A. et al, (2014) Journal Experimental Botany



Meroni, M. et al, (2009) Remote Sensing of Environment

flex

Several global datasets have appeared from serendipity…



(c) GOME-2 (left) and GOSAT (right), Annual 2009

- Potentially useful, even if it might only be a better 'green APAR’
- Coarse spatial resolution: 0.5 degrees

  (but downscaled product exist … come to the practical lesson!)

Other avenues worth exploring…

NIRv: Index multiplying NIR times NDVI seems to provide high correlation with SIF/GPP (*Badgley, Field, Berry, Sci. Adv. 2017*), advantage of having longer archive & higher res.

Photochemical Reflectance Index (PRI): Normalized difference between leaf reflectance at 531 nm and a reference wavelength (~550 nm) (*Gamon et al. 1992*)

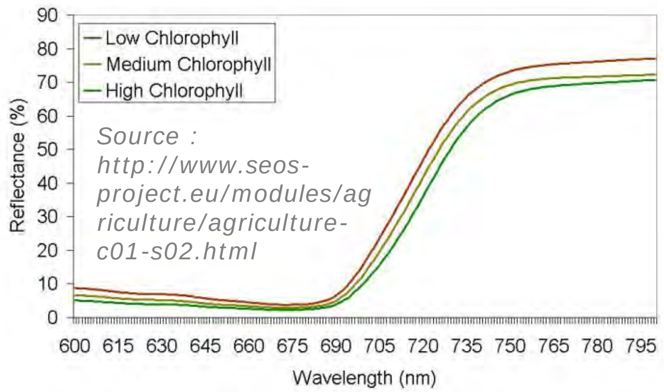
⇒ Related to xanthophyll cycle

⇒ can serves as proxy for LUE

Bands in the RED EDGE: region of rapid change in reflectance of vegetation between red and near infrared (690-730 nm)

⇒ recognized as key for improving chlorophyll retrieval

⇒ *Sentinel-2* has 2 bands in the red edge



Source : http://www.seos-project.eu/modules/agriculture/agriculture-c01-s02.html

(Above-Ground) Biomass [AGB] from space

- Requires space-borne lidar to estimate AGB from tree height
- Assume global or continental allometric relationships (AGB varies only with stand height
- Fusion of 2 maps along with ground AGB estimates:

NEW MISSIONS COMING UP:
- *NASA GEDI*
- *ESA BIOMASS*

Avitabile, V., et a\l. (2016). An integrated pan-tropical biomass map using multiple reference datasets. Global Change Biology, 22(4), 1406–1420.

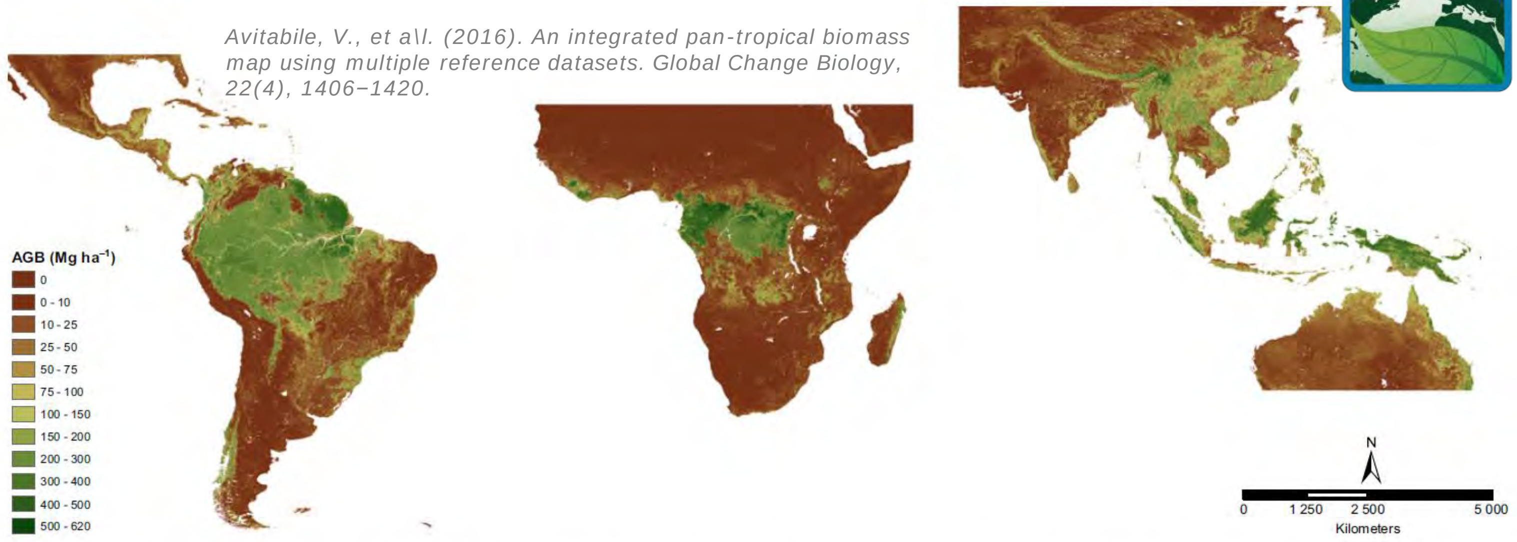


Fig. 3 Fused map, representing the distribution of live woody aboveground biomass (AGB) for all land cover types at 1-km resolution for the tropical region.

VOD – Vegetation Optical Depth

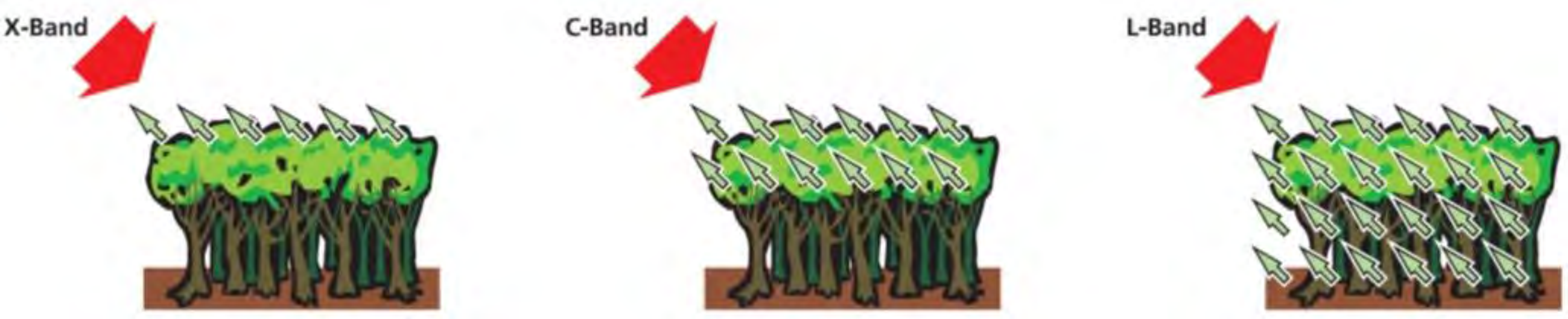
Passive microwave sensors are used for estimating soil moisture

But they need to 'model' and estimate 'noise' from the vegetation above

This 'noise' is in fact useful to relate to wet canopy structure

Not all bands penetrate as much...

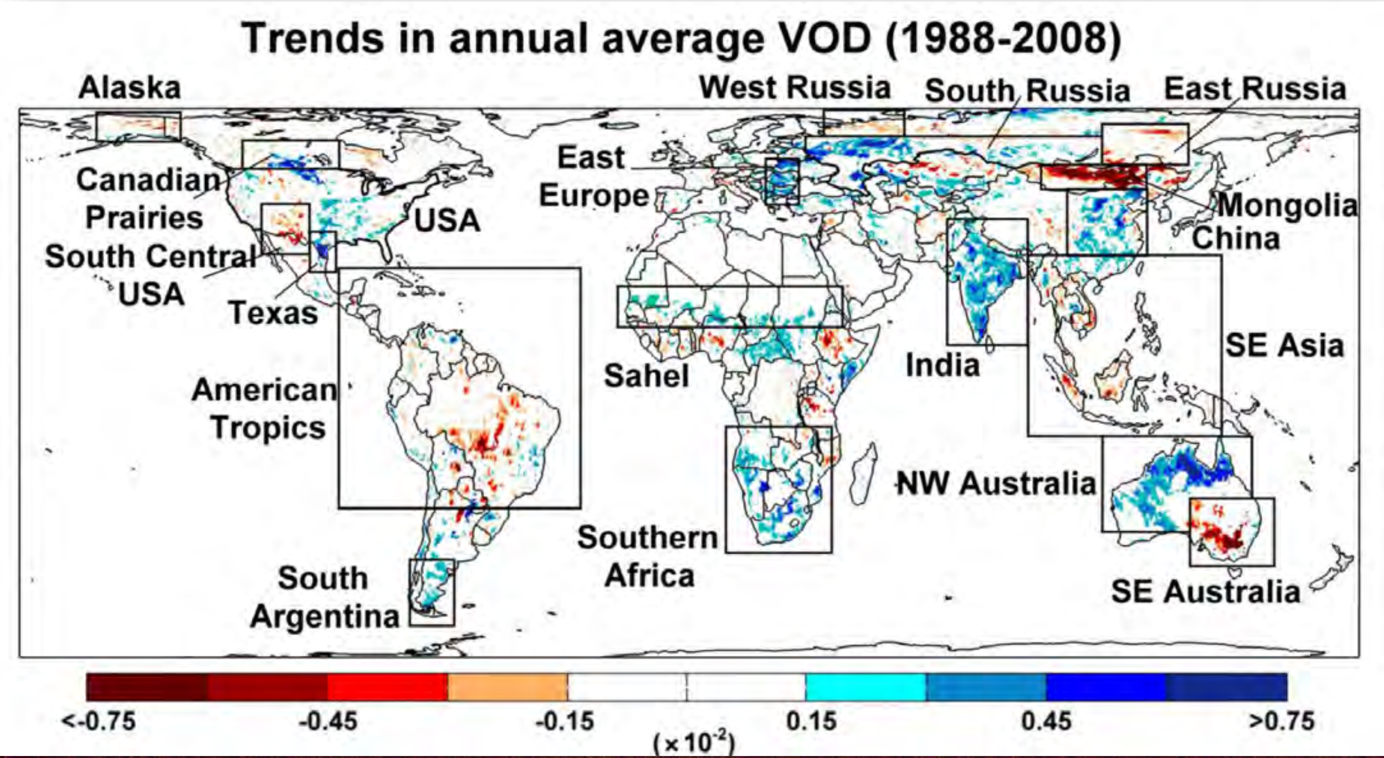
Source: http://www.dlr.de/hr/en/desktopdefault.aspx/tabid-8113/14171_read-35852/



VOD from C-band

Long time series of above-ground biomass change estimated from VOD

But arguably does not penetrate enough...

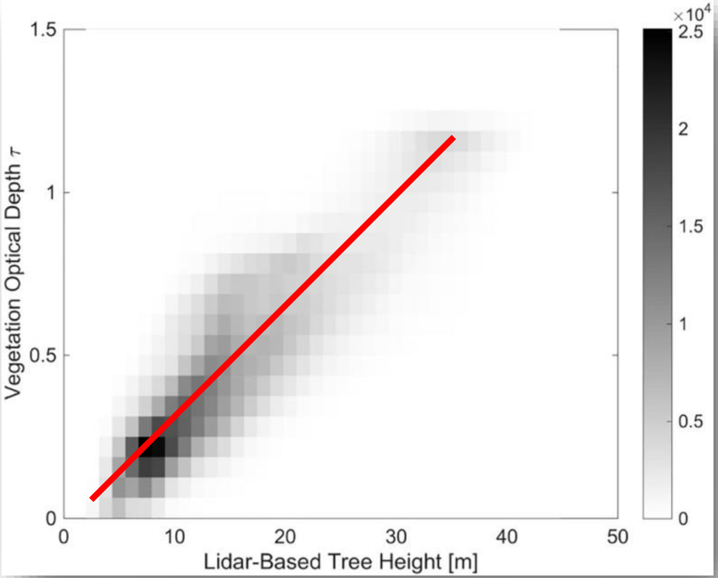


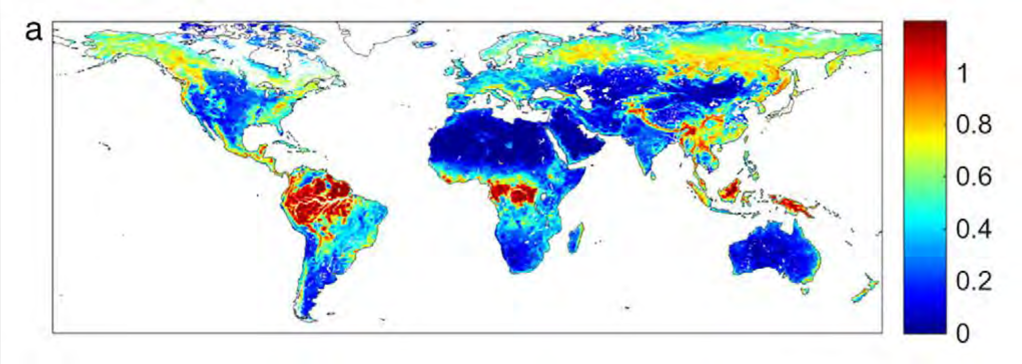
Liu. Y.Y.,et al (2013), Global Ecology and Biogeography

VOD from L-band sensors (SMOS, SMAP)

Show some promise of better results.

But time series are very short (couple of years)...





Konings, A. G., Piles, M., Das, N., & Entekhabi, D. (2017). L-band vegetation optical depth and effective scattering albedo estimation from SMAP. Remote Sensing of Environment, 198, 460–470. https://doi.org/10.1016/j.rse.2017.06.037

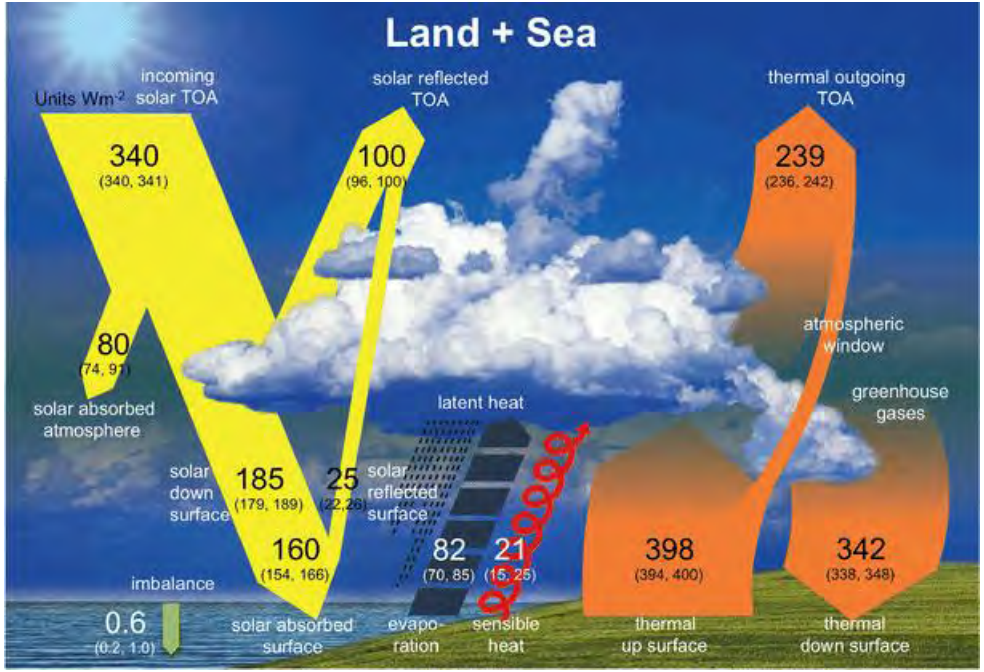
The surface energy balance (SEB)

Radiative vs non-radiative (turbulent) fluxes

$$SW + LW = LE + H + G$$

$$SW_{down} - SW_{up} + LW_{down} - LW_{up} = LE + H + G$$

$$SW_{down}(1 - \alpha) + LW_{down} - LW_{up} = LE + H + G$$



Wild et al. 2015. Clim. Dynamics

Surface Albedo

- How much shortwave radiation is reflected by the surface
- Obtained from multi-angular observations over a moving window
- Algorithms provide black-sky (directional) albedo and vs white-sky (diffuse) albedo
- Shortwave broadband or provided per spectral band (BRDF correction)

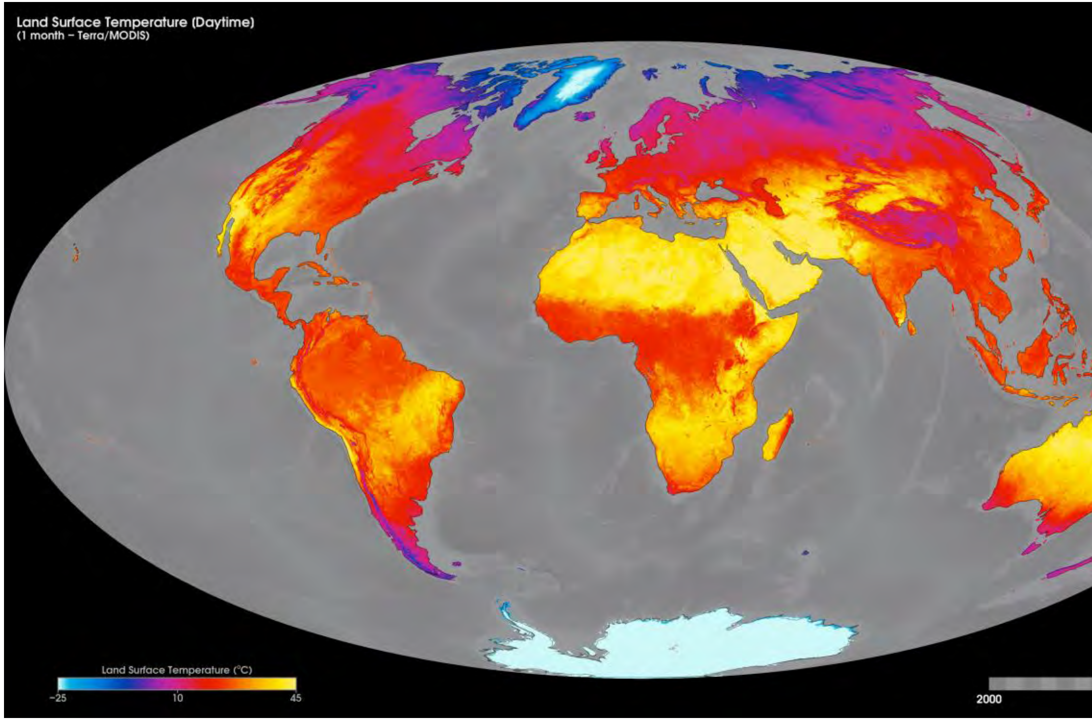
http://modis.gsfc.nasa.gov

Land surface temperature (LST)

- Radiant temperature in Kelvin
- Variable resuming the consequence of the energy balance
- Linked to LW by Stephen-Boltzmann law

$$LW = \varepsilon \sigma T^4$$

- Obtained from multi-angular observations of TIR reflectance
- Ill-posed problem inversion



Evapotranspiration or Latent Heat

Penman-Monteith equation

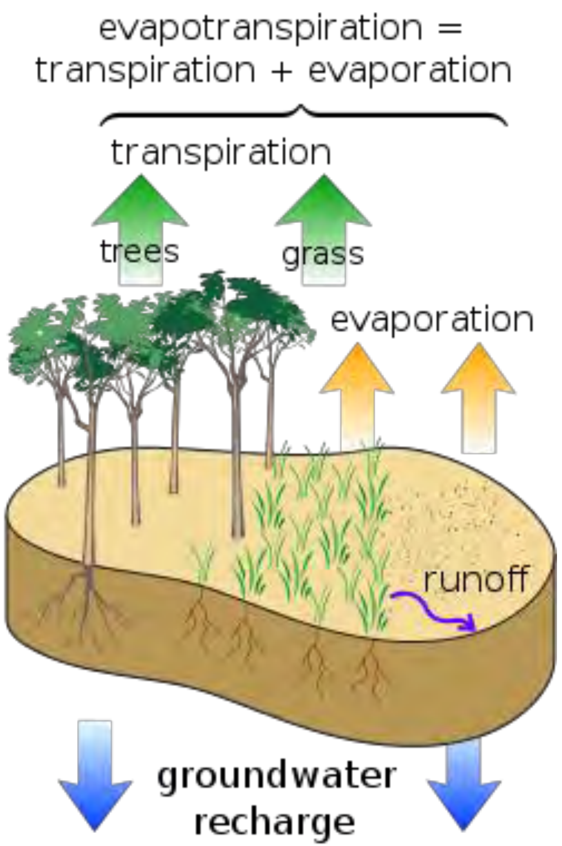
$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Priestly-Taylor equation

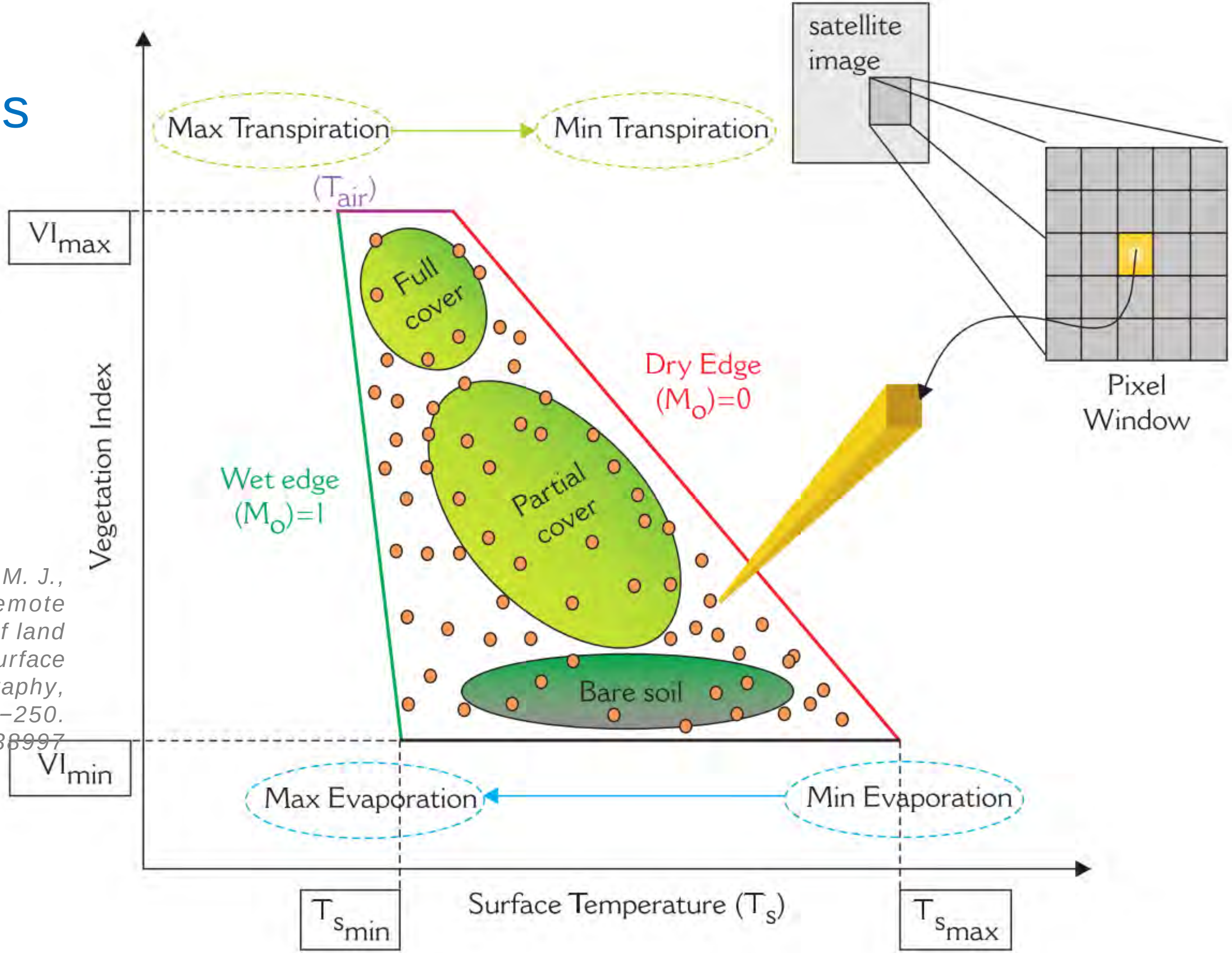
$$\mathrm{ETp} = \alpha \frac{\Delta}{\Delta + \gamma} (\mathrm{Rn} - \mathrm{G}) \qquad [1]$$

Some existing products:

MOD16,

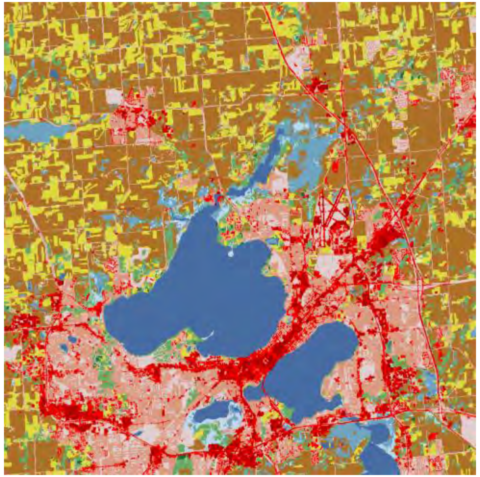


Estimating ET from LST + VIs



Petropoulos, G., Carlson, T. N., Wooster, M. J., & Islam, S. (2009). A review of Ts/VI remote sensing based methods for the retrieval of land surface energy fluxes and soil surface moisture. Progress in Physical Geography, 33(2), 224–250. doi:10.1177/0309133309338997

Description of the land surface



Land Cover = physical material at the surface of the earth
(grass, asphalt, trees)

high resolution land cover cci

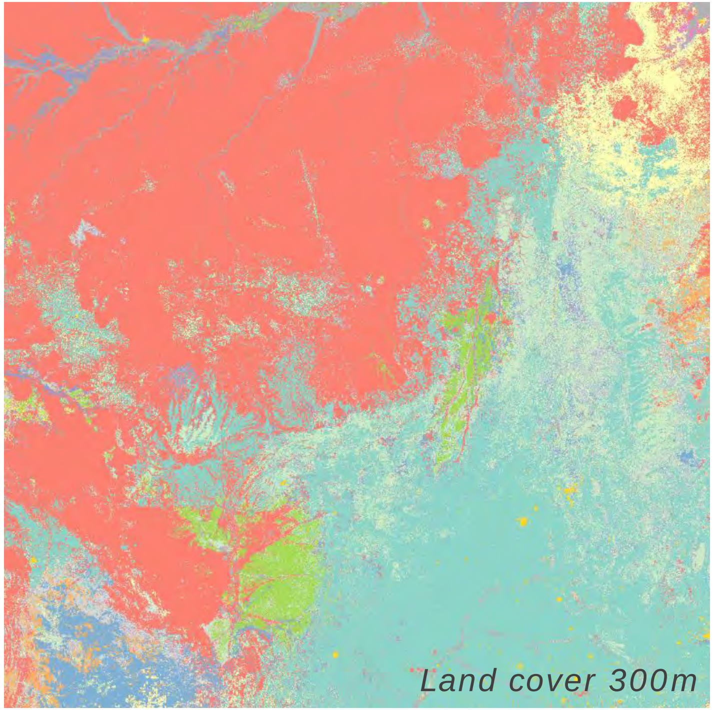
Land Use = description of how people *utilize* the land
(wheat field, short-rotation coppice, ...)

Plant Functional Types = group of plants based on common features:
- structural (grasses/shrubs/trees),
- physiological (broadleaf/needleleaf)
- phenological (deciduous/evergreen)

Optically distinguishable functional types = based on detectable traits

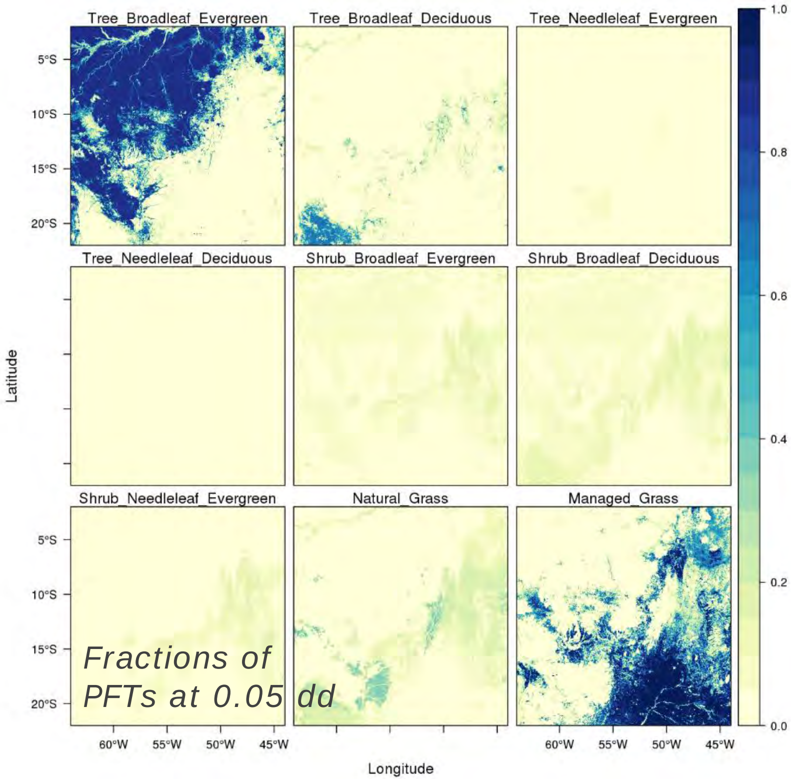
Ustin, S. L., & Gamon, J. A. (2010). Remote sensing of plant functional types. The New Phytologist, 186(4), 795–816. https://doi.org/10.1111/j.1469-8137.2010.03284.x

From land cover to plant functional types (PFTs)



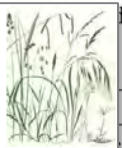
Land cover 300m

ESA CCI



Fractions of PFTs at 0.05 dd

Table 2. Default land cover to plant functional ty[…] […]ded by […]e 22 […]d 14 level 2 UNLCCS sub-classes in italics. The units are % coverage of each PFT per […]



LCCS Class	UNLCCS Land Cover Class Description												Non-vegetated		
				NeEv					NeDe			[…] soil	Water	Snow/Ice
10	Cropland, rainfed										100			
11	*Herbaceous cover*										100			
12	*Tree or shrub cover*						50				50			
20	Cropland, irrigated or post-flooding										100			
	[…]) (< 50 %)	5				5		5			60			
	[…]d (< 50 %)	5				7.5	10	7.5			40			
	[…]5 %)	90				5	5							
	[…]5 %)		70				15			15				
			70				15			15				
			30				25			35		10		
70	Tree cover, needleleaf, evergreen, closed to open (> 15 %)			70		5	5	5		15				
71	*Tree cover, needleleaf, evergreen, closed (> 40 %)*			70		5	5	5		15				
72	*Tree cover, needleleaf, evergreen, open (15–40 %)*			30			5	5		30		30		
80	Tree cover, needleleaf, deciduous, closed to open (> 15 %)				70	5	5	5		15				
81	*Tree cover, needleleaf, deciduous, closed (> 40 %)*				70	5	5	5		15				
82	*Tree cover, needleleaf, deciduous, open (15–40 %)*				30		5	5		30		30		
90	Tree cover, mixed leaf type (broadleaf and needleleaf)		30	20	10	5	5	5		15		10		
100	Mosaic tree and shrub (> 50 %)/herbaceous cover (< 50 %)	10	20	5	5	5	10	5		40				
110	Mosaic herbaceous cover (> 50 %)/tree and shrub (< 50 %)	5	10	5		5	10	5		60				
120	Shrubland					20	20	20		20		20		
121	*Shrubland evergreen*					30		30		20		20		
160	Tree cover, flooded, fresh or brackish water	30	30							20			20	
170	Tree cover, flooded, saline water	60				20							20	
180	Shrub/herbaceous cover, flooded, fresh/saline/brackish water		5	10			10	5		40			30	
190	Urban areas		2.5	2.5						15		75	5	
200	Bare areas											100		

Tree cover, broadleaf, deciduous, closed to open (>15%)

But this transformation should not be necessary if we have 'optical functional types' or if we produce continuous maps of vegetation cover directly

Climate modelling: some clarifications...

LSMs [Land surface models]: models biogeophysical and biogeochemical interactions between the land and the atmosphere.

DGVMs [Dynamic global vegetation model]: models potential vegetation and its associated biogeochemical and hydrological cycles as a response to shifts in climate. *(often equivalent to LSM with dynamic vegetation but sometimes has no biophysics)*

GCMs [General Circulation Models]: models the general circulation of a planetary atmosphere (AGCM) or ocean (OGCM) or both (AOGCM). Includes an LSM/DGVM.

IAMs [Integrated Assessment Models]: models socio-economic interactions and their responses to forced climate (eg. from GCMs). Used to make scenarios (SSPs and RCPs)

ESMs [Earth System models]: models full Earth system, i.e. physical processes like an AOGCM but also includes human interactions such as land use change

By NOAA [Public domain or Public domain], via Wikimedia Commons

Role of remote sensing for climate science

- Full potential has been neglected to some extent by climate community

Some downsides…

- no direct observation of carbon
- Requires archive… often too short…
- Cannot go in the future under difference scenarios

Major strengths…

- Synoptic coverage ➔ can bridge the gap between *in situ* and models
- Could be a baseline for a revisited bottom-up approach to vegetation modelling

Thank you for your attention…

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@GregDuveiller