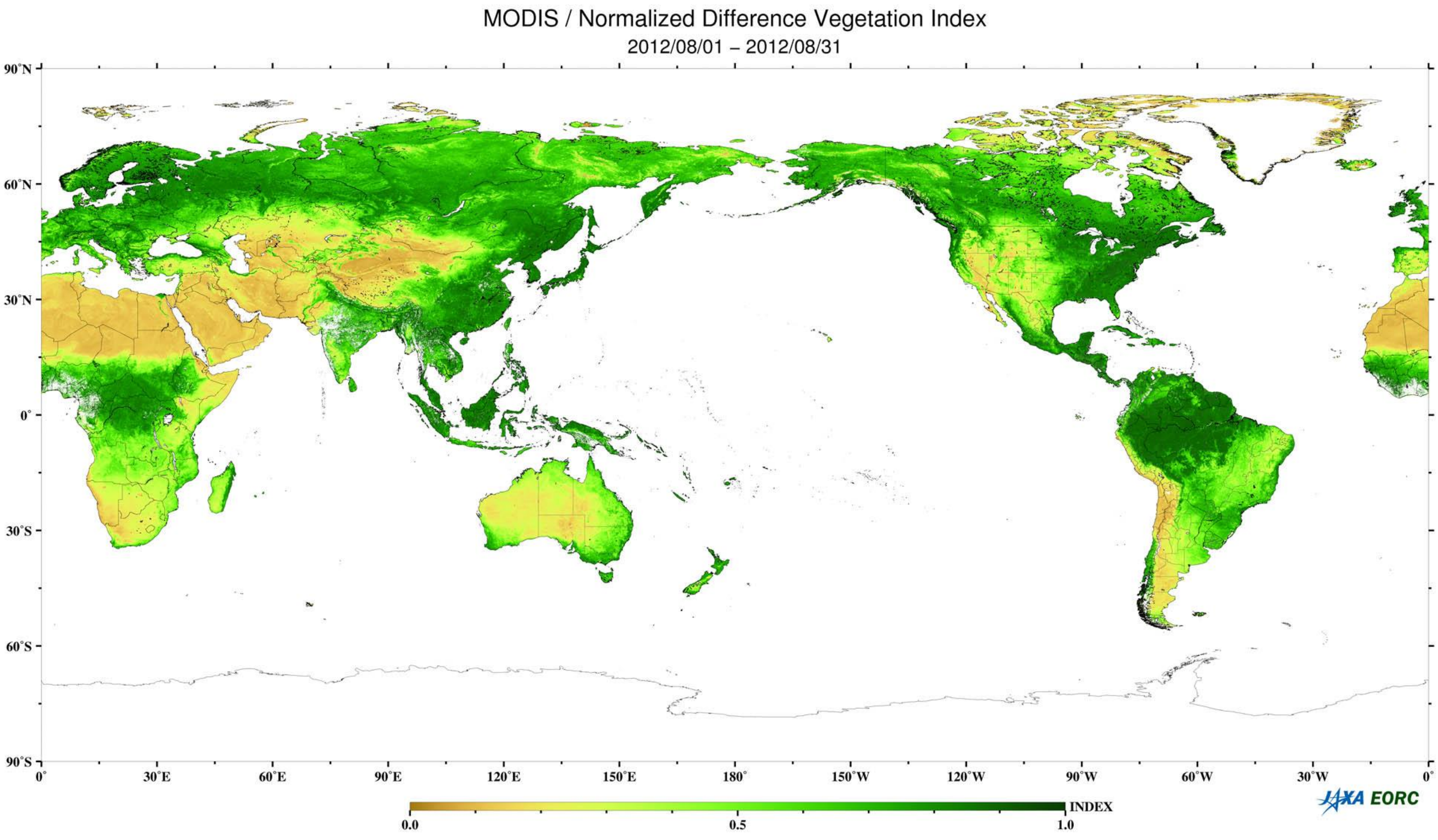
Carbon and NPP!

NPP and NEP

- Topics
  - Respiration, production, and storage etc.
  - Approaches
  - How can remote sensing help?
  - What has been done in this area?
  - What are the limitations?



http://www.eorc.jaxa.jp/en/imgdata/topics/2014/tp140317.html

GPP

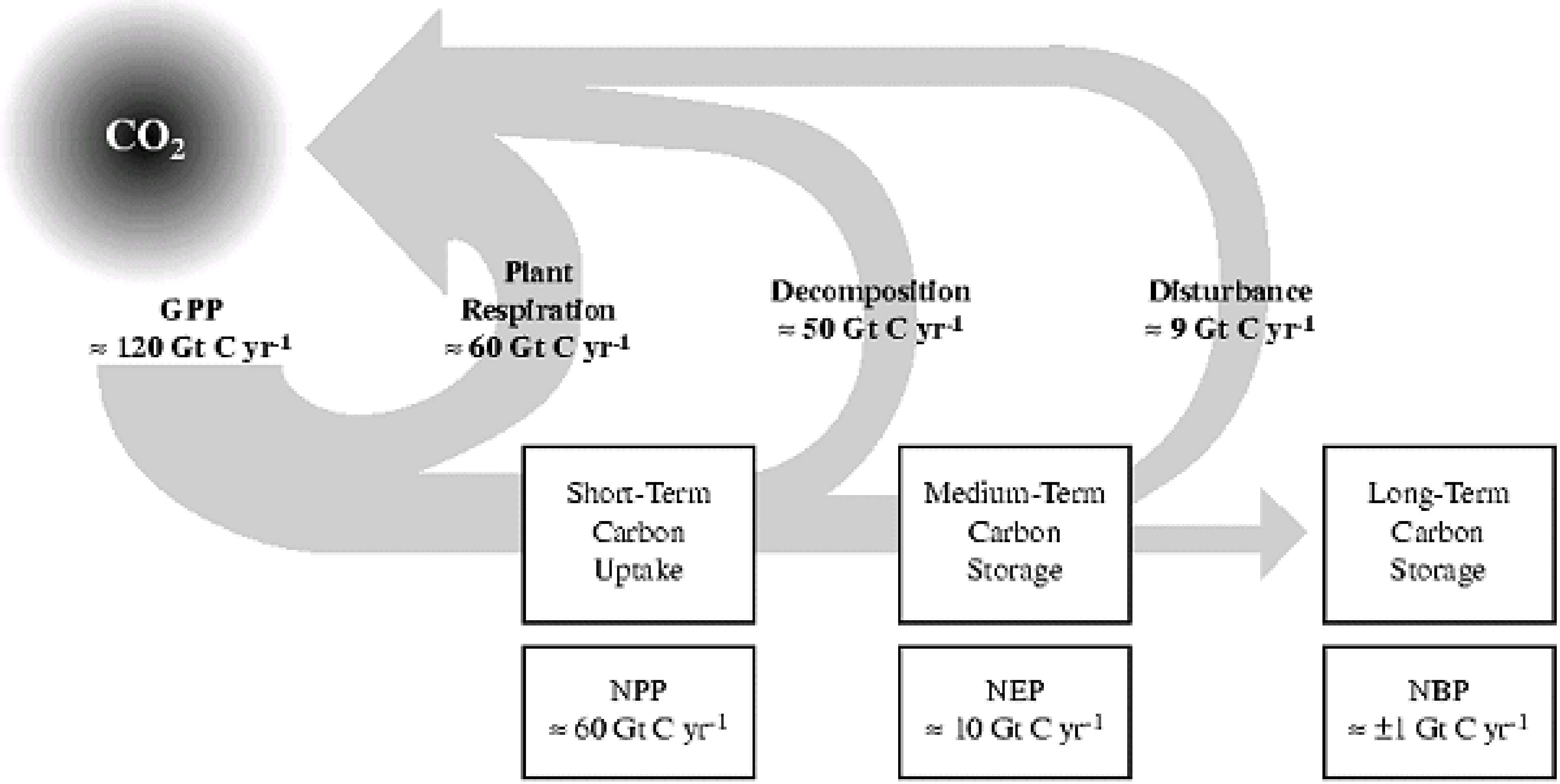
- *Gross Primary Production* denotes the total amount of carbon fixed in the process of photosynthesis by plants in an ecosystem, such as a stand of trees.
- GPP is measured on photosynthetic tissues, principally leaves. Global total GPP is estimated to be about 120 Gt C yr^{-1}.

NPP

- *Net Primary Production* denotes the net production of organic matter by plants in an ecosystem—that is, GPP reduced by losses resulting from the respiration of the plants (autotrophic respiration).
- Global NPP is estimated to be about half of the GPP—that is, about 60 Gt C yr^{-1}.

NEP

- *Net Ecosystem Production* denotes the net accumulation of organic matter or carbon by an ecosystem; NEP is the difference between the rate of production of living organic matter (NPP) and the decomposition rate of dead organic matter (heterotrophic respiration, RH).
- Heterotrophic respiration includes losses by herbivory and the decomposition of organic debris by soil biota. Global NEP is estimated to about 10 Gt C yr^{-1}.
- NEP can be measured in two ways: One is to measure changes in carbon stocks in vegetation and soil; the other is to integrate the fluxes of CO_2 into and out of the vegetation (the net ecosystem exchange, NEE) with instrumentation placed above (Aubinet *et al.*, 2000).



- *Global terrestrial carbon uptake. Plant (autotrophic) respiration releases CO2 to the atmosphere, reducing GPP to NPP and resulting in short-term carbon uptake. Decomposition (heterotrophic respiration) of litter and soils in excess of that resulting from disturbance further releases CO2 to the atmosphere, reducing NPP to NEP and resulting in medium-term carbon uptake. Disturbance from both natural and anthropogenic sources (e.g., harvest) leads to further release of CO2 to the atmosphere by additional heterotrophic respiration and combustion—which, in turn, leads to long-term carbon storage (adapted from Steffen et al., 1998).*

NBP

- *Net Biome Production* denotes the net production of organic matter in a region containing a range of ecosystems (a biome) and includes, in addition to heterotrophic respiration, other processes leading to loss of living and dead organic matter (harvest, forest clearance, and fire, etc.) (Schulze and Heimann, 1998).
- NBP is appropriate for the net carbon balance of large areas (100–1000 km^2) and longer periods of time (several years and longer). In the past, NBP has been considered to be close to zero.
- Compared to the total fluxes between atmosphere and biosphere, global NBP is comparatively small; NBP for the decade 1989–1998 has been estimated to be 0.7 ± 1.0 Gt C yr^{-1} (Table 1)-about 1 percent of NPP and about 10 percent of NEP.

	1980 to 1989	1989 to 1998
1) Emissions from fossil fuel combustion and cement production	5.5 ± 0.5	6.3 ± 0.6(a)
a) from Annex I countries[d]	3.9 ± 0.4[a]	3.8 ± 0.4[a]
i) from countries excluding those with economies in transition	2.6 ± 0.3	2.8 ± 0.3
ii) from countries with economies in transition(d)	1.3 ± 0.3[a]	1.0 ± 0.3[a]
b) from rest of world[d]	1.6 ± 0.3[a]	2.5 ± 0.4[a]
2) Storage in the atmosphere	3.3 ± 0.2	3.3 ± 0.2[b]
3) Ocean uptake	2.0 ± 0.8	2.3 ± 0.8[c]
4) Net terrestrial uptake = (1) – [(2)+(3)]	0.2 ± 1.0	0.7 ± 1.0
5) Emissions from land-use change	1.7 ± 0.8[e]	1.6 ± 0.8[f]
6) Residual terrestrial uptake = (4)+(5)	1.9 ± 1.3	2.3 ± 1.3

The uncertainty ranges in (Table 1) result partly from our limited ability to determine accurately the gradual changes in the carbon balance resulting from human-induced emissions. variations in the atmospheric CO_2 growth rate that have been recorded since 1960 imply that global terrestrial and oceanic carbon sources and sinks may vary significantly in time (Conway *et al.*, 1994; Francey *et al.*, 1995; Keeling *et al.*, 1996a).

Fossil fuel emissions, on the other hand, do not fluctuate much from one year to the next, whereas the exchange of atmospheric CO_2 with the oceans and the terrestrial biosphere responds to inter-annual climate variations.

High atmospheric CO_2 growth rates have been recorded during three recent El Niño events—in 1983, 1987, and 1998—indicating a lower than normal uptake of atmospheric CO_2 by the terrestrial biosphere and the oceans (Gaudry *et al.*, 1987; Keeling *et al.*, 1989; Keeling and Whorf, 1999). Conversely, low atmospheric CO_2 growth rates were observed between 1991 and 1993, indicating enhanced uptake—particularly over the northern hemisphere (Ciais *et al.*, 1995a,b; Keeling *et al.*, 1996b).

- Ocean carbon models and available data suggest that the oceans contribute less to observed year-to-year changes in atmospheric CO2 concentration than does the terrestrial biosphere (Winguth *et al.*, 1994; Le Quéré *et al.*, 1998; Lee *et al.*, 1998; Feely *et al.*, 1999; Rayner *et al.*, 2000).

- The terrestrial biosphere therefore appears to drive most of the inter-annual variation in CO2 flows. The way ecosystems respond to climate variability is not well understood, although the correlation and lag-correlation of inter-annual variability between CO2 growth rates, climate, and the remotely sensed "greenness" normalized difference vegetation index (NDVI), which is related to photosynthesis, is illustrative (Braswell *et al.*, 1997; Myneni *et al.*, 1997).

- When terrestrial biogeochemical models are forced with realistic year-to-year changes in temperature and precipitation, they can simulate changes in the global and regional biosphere and associated changes in CO2 exchange with the atmosphere (Kindermann *et al.*, 1996; Tian *et al.*, 1998).

- These models can reproduce the magnitude and to some extent the phase of observed inter-annual variability of atmospheric CO2 concentrations, though different processes have been implicated in attempts to explain the observed fluctuations (e.g., Heimann *et al.*, 1997). There are still differences in detail that have not been resolved.

- Shifts in magnitude and phase of atmospheric CO2 fluctuations on a decadal time scale suggest that seasonality of terrestrial biotic fluxes has been changing slowly at mid to high northern latitudes (Keeling *et al.*, 1996b; Randerson *et al.*, 1997).

- Remotely sensed data (Myneni *et al.*, 1997), as well as phenological observations (Menzel and Fabian, 1999), independently indicate a longer growing season in the boreal zone and in temperate Europe during recent decades.

- [a] Based on emission estimates through 1996 by Marland *et al*. (1999) and estimates derived from energy statistics for 1997 and 1998 (British Petroleum Company, 1999).
- [b] Based on atmospheric CO2 concentrations measured at Mauna Loa, Barrow, and South Pole (Keeling and Whorf, 1999).
- [c] Based on ocean carbon cycle model (Jain *et al*., 1995) used in the IPCC Second Assessment Report (IPCC, 1996; Harvey *et al*., 1997) consistent with an uptake of 2.0 Gt C yr^{-1} in the 1980s.
- [d] Annex 1 countries and countries with economies in transition (a subset of Annex 1 countries) defined in the FCCC. Emissions include emission estimates from geographic regions preceding this designation and include emissions from bunker fuels from each region.
- [e] Based on land-use change emissions estimated by Houghton (1999) and modified by Houghton *et la*.(1999, 2000), which include the net emissions from wood harvesting and agricultural soils.
- [f] Based on estimated annual average emissions for 1989–1995 (Houghton *et al*., 1999, 2000).

(Daily) net photosynthesis (PSN) and (annual) net primary production (NPP)

PSN and NPP

- (**daily**) net photosynthesis (PSN)
- (**annual**) net primary production (NPP)

- related to net carbon uptake
  - important for understanding global carbon budget (climate change)
  - Increased CO2, climate change? Increased veg. growth?

PSN and NPP

- $C0_2$ removed from atmosphere
  – **photosynthesis**
- $C0_2$ released by plant (and animals)
  – **respiration**
- Net Photosynthesis (PSN)
  - net carbon exchange over 1 day: (photosynthesis - respiration)
  - i.e. NOT emitted CO_2

PSN and NPP

- **Net Primary Productivity** (NPP)
  - annual net carbon exchange
  - quantifies actual plant growth
  - (not just $C0_2$ fixation)

Algorithms - require to be model-based

- simple production efficiency model (PEM)
  - (Monteith, 1972; 1977)
- relate PSN, NPP to APAR
- APAR from PAR and fAPAR

- i.e. APAR = Σ incoming * fraction absorbed

Extra reading

- http://nacarbon.org/nacp/documents/Our-Changing-Planet_FY-2016_full%202.pdf
- https://downloads.globalchange.gov/strategic-plan/2012/usgcrp-strategic-plan-2012.pdf
- https://carboncyclescience.us/state-carbon-cycle-report-soccr
- http://nacarbon.org/nacp/documents.html?#ccs
- http://nacarbon.org/nacp/documents.html?#ccsp
- http://www.ntsg.umt.edu/

$$PSN = \varepsilon * APAR$$

$$NPP = \varepsilon * \sum APAR$$

- PSN = daily total photosynthesis
- NPP, PSN typically accum. of dry matter (DM) (convert to C by assuming DM 48% C)
- ε = efficiency of conversion of PAR to DM (g/MJ)
- equations hold for non-stressed conditions

To characterise vegetation need to know:

- Efficiency (ε) and *fAPAR*
  – But……..fAPAR ∝ NDVI
- So, for fixed ε
- So $$NPP \propto \varepsilon * \sum (NDVI * \int_{day} IPAR)$$
- incident solar radiation (IPAR) also from RS (Dubayah, 1992)

Determining ε

- herbaceous vegetation (grasses):
  - av. 1.0-1.8 gC/MJ for C_3 plants, higher for C_4
- woody vegetation:
  - 0.2 - 1.5 gC/MJ
- simple model for ε:

$$\varepsilon = \varepsilon_{gross} * f * Y_g * Y_m$$

Determining ε

$$\varepsilon = \varepsilon_{gross} * f * Y_g * Y_m$$

- ε_{gross} = conversion efficiency of gross photosyn. (= 2.7 gC/MJ)
- f - fraction of daytime when photosyn. not limited (base temp. etc)
- Y_g - fraction of photosyn. NOT used by growth respiration, GR, (65-75%)
- Y_m - fraction of photosyn. NOT used by maintenance respiration, MR, (60-75%)

- define $\varepsilon_{\max}$ - max. efficiency

$$\varepsilon_{\max} = \varepsilon_{gross} * Y_g * Y_m$$

- so

$$\varepsilon = f * \varepsilon_{\max}$$

$\varepsilon_{\max}$ - determined by plant form

- f - determined by climate
  - base / max temperature
  - water or other stresses - light availability

Productivity algorithm

- Estimate ε_{max} - land cover
  - LUT for biome characteristics

- Estimate *f* - climatological inputs
  - can link to index of temperature/moisture stress from surf. temp / VI

- also require global Met. data (IPAR, rainfall)

MODIS PSN/NPP algorithm

- MODIS Product No. 17
  - Photosynthesis (PSN) 1km spatial, 8 day temporal resolution
  - Net Primary Productivity (NPP) 1km spatial, annual
- *Daily:*
  - pixel-wise gross primary productivity terms computed and stored
- *8 day:*
  - pixel-wise gross primary productivity terms computed and stored
  - ***8-day compositing*** routine - (8) contiguous daily products composited to produce a single PSN or NPP 1KM global data product.
- *Annual:*
  - ***annual NPP compositing*** routine $\Rightarrow$ 1KM global annual data product, based on (365) day accumulated sum of GPP less maintenance respiration (gpp - rm) term.

- Before 1980, biology focused at organismal level and ecological studies were carried out at 0.1 hectare field plots

- Lieth and Whittaker, 1975; produced a coarse global GPP map.

- When synoptic regional remote sensing began, field ecologists combined traditional measurements of plant biomass, primary productivity, canopy height and other ecological variables with satellite derived greenness to obtain the first global estimates of GPP.

Theory behind modeling GPP

1) plant NPP is directly related to absorbed solar energy

2) a connection exists between absorbed solar energy and satellite derived spectral indices of vegetation

3) assumption that there will be biophysical reasons why the absorbed light energy may be reduced below the theoretical potential value.

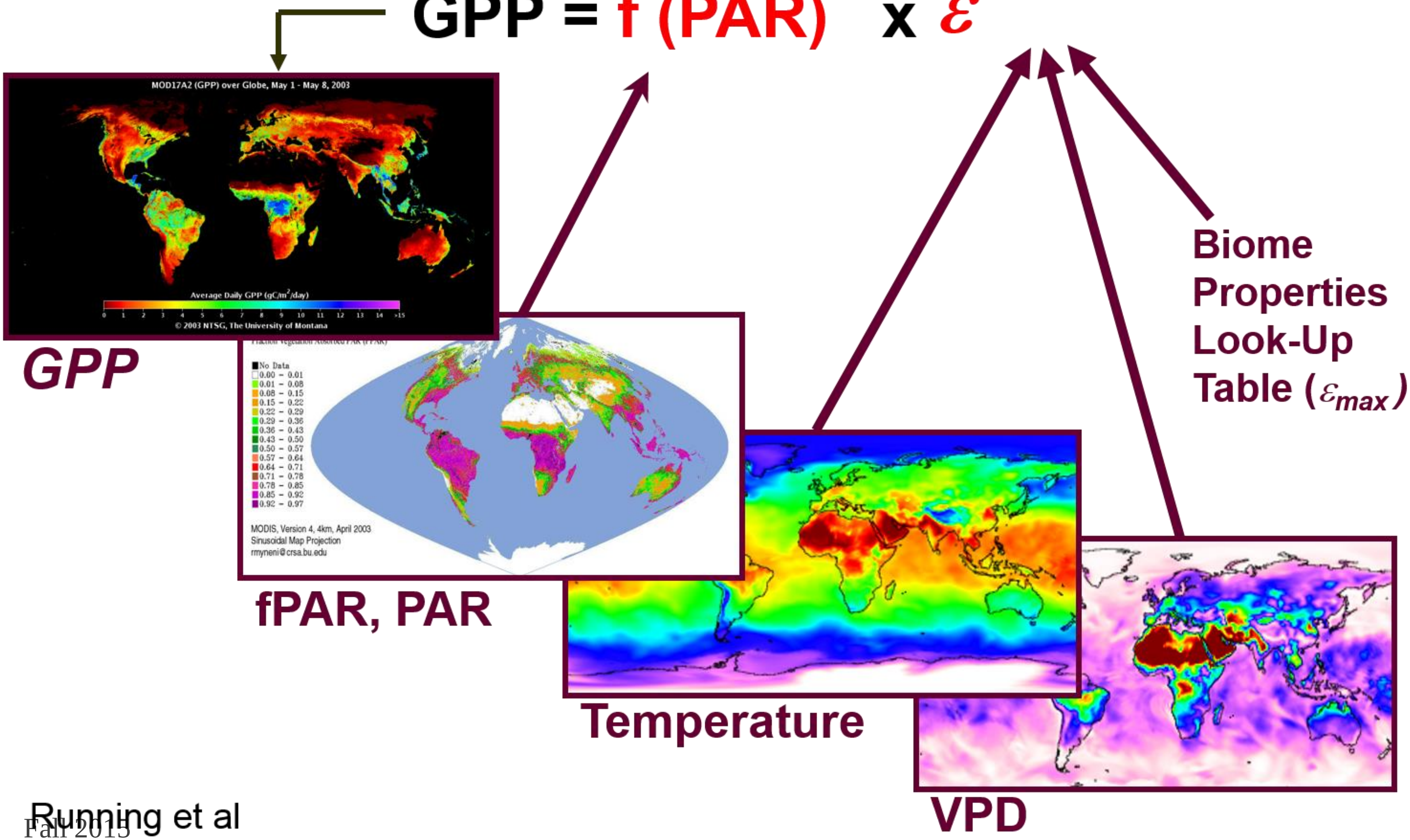
conceptual basis for modeling GPP

- Monteith's light use efficiency (ε) is usually defined as the mass of carbon uptake per absorbed photosynthetically active radiation (APAR) from 400 nm to 700 nm wavelength.

- Gross primary production (GPP, g C m^2 $time^{-1}$) is summed over time periods ranging from instantaneous fluxes to annual totals

GPP = Light X Conversion Efficiency

$$GPP = f(PAR) \times \varepsilon$$



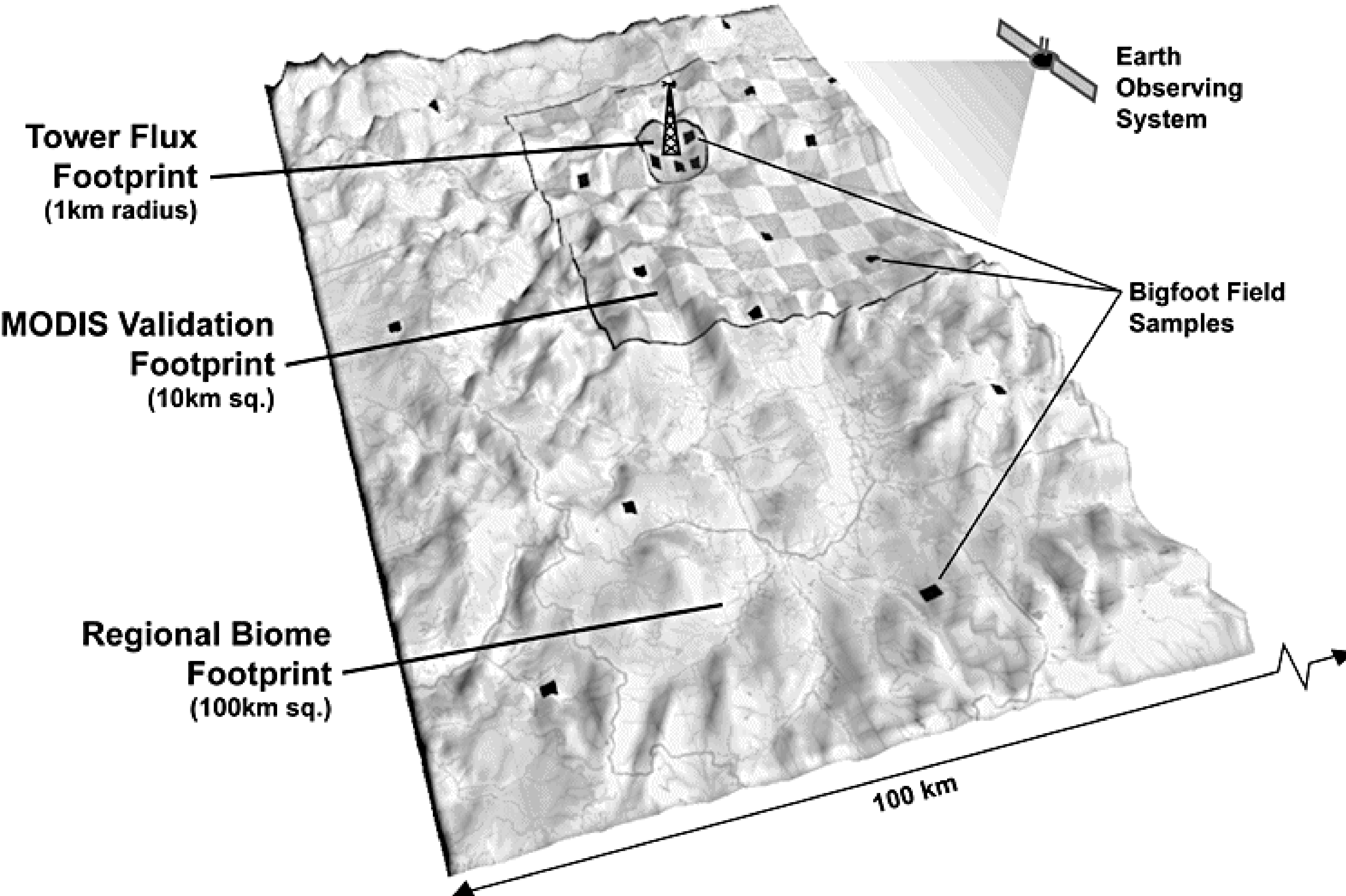
Running et al

- GPP = ε Σ APAR
- NDVI = (NIR –Red) / (NIR +Red)
- APAR/PAR = NDVI
- fPAR = APAR/PAR = NDVI
- GPP = ε x fPAR x PAR
- **GPP = ε x NDVI x PAR**

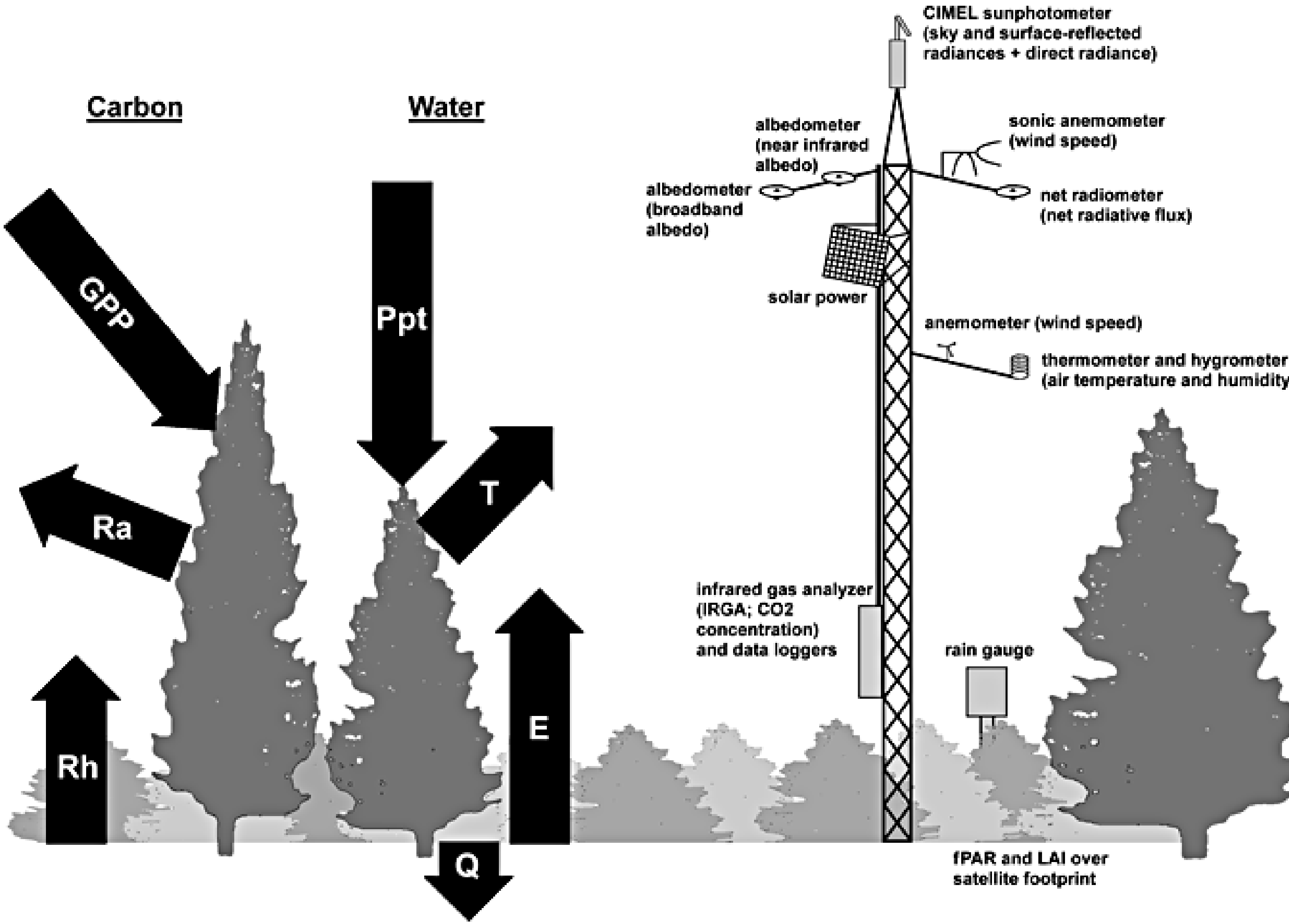
  where ε is the efficiency of light use and APAR is Absorbed Photosynthetically Active Radiation. The LUE model defines the components of GPP for a given time period as total APAR and the LUE coefficient (ε)

GPP_{MODIS} = *ε*max x m(*T*min) x m(*VPD*) x *f*PAR x SWrad x 0.45

'Big Foot' scaling exercise



FLUXNET CONFIGURATION



- **VPM**
- $fPAR_{canopy} = fPAR_{chl} + fPAR_{NPV}$
- The VPM differs slightly from the MODIS GPP equation. Instead of the BPLUT look up table, derived from BIOME-BGC, εg is obtained from remote sensing and meteorological inputs as follows:

- $GPP = \varepsilon g \times fPAR_{chl} \times PAR$ where

  $\varepsilon g = \varepsilon 0 \times T_{scalar} \times W_{scalar} \times P_{scalar}$

  where PAR is the photosynethically active radiation (μmol/m2/s, photosynthetic photon flux density), $fPAR_{chl}$ is the fraction of PAR absorbed by chlorophyll, εg is the light use efficiency, LUE (μmol CO_2/ μmol PAR).

- The parameter ε0 is the maximum light use efficiency (μmol CO_2/ μmol PAR), and T_{scalar}, W_{scalar}, and P_{scalar} are the regulation scalars for the effects of temperature, water and leaf phenology on the light use efficiency of vegetation. On average, ε0 has a value around 1/6 for well-watered, C3 plants at optimal temperatures

Vegetation Indices

- Enhanced Vegetation Indices:

$$E = G \times \frac{\rho_{NIR} - \rho_{\mathrm{Re}\,d}}{\rho_{NIR} + C_1 \times \rho_{\mathrm{Re}\,d} - C_2 \times \rho_{Blue} + L}$$

ρ_{NIR}, ρ_{Red} and ρ_{Blue} = atmospherically corrected surface reflectance

L = canopy background brightness correction factor (1)

C1 and C2 = atmospheric resistance Red and Blue correction coefficients (6&7.5)

G = Gain factor (2.5)

- Huete et al., 2002

- fPARchl = *a* x EVI*
- LSWI* = (ρred – ρswir) / (ρred + ρswir)
- Wscalar = 1 + LSWI / 1 + $LSWI_{max}$
- Pscalar = 1 + LSWI/2, during bud burst to full expansion of leaf (decid. Forests) i.e.Spring
- Pscalar = 1, after leaf expansion (also for evergreen forests & grasslands) peak growing season to fall

- *Enhanced Vegetation Index
- *Land Surface Water Index

- T_{scalar} is sensitivity of photosynthesis to temperature, calculated at 8-day time step using an equation developed for the Terrestrial Ecosystem Model*.
- $T_{scalar} = (T - T_{min})(T - T_{max}) / [(T - T_{min})(T - T_{max}) - (T - T_{opt})^2]$
- where T_{min}, T_{max}, and T_{opt} are minimum, maximum, and optimal temperatures (˚C) for photosynthesis, respectively. If air temperature falls below T_{min}, T_{scalar} is set to zero
- Pscalar & Wscalar optimized for grasslands was changed to reflect deciduous nature of *Populus spp.*and *Artemisia ordosica at K04 & 5*

Modified Vegetation Photosynthesis Model (MVPM)

- Early LUE models assumed that LUE was constant; recent studies have shown that LUE varies considerably across ecosystem types and disturbance such as drought and diffuse albedo
- Cascading error in estimating LUE LUT from coarse res. (1˚ x 1.25˚ pixel) DAO data
- studies suggested that independent measures of LUE were unnecessary as they found good correlations between spectral indices with carbon fluxes as well as with LUE
- much simpler from processing point of view to create a GPP model entirely on remotely sensed data of similar resolution.
- it remains unclear as to what extent can short term variability in carbon fluxes be estimated through spectral indices

- some scaling up studies in semi-arid areas using correlations between NDVI and carbon fluxes carried out but not across different ecosystem types
- VPM is not entirely independent of ground based sensor measurements such as PAR and temperature
- studied the feasibility of replacing these variables with MODIS derived GPP, fPAR and LST products

- $GPP = \boldsymbol{\alpha}\ [\ln (GPP_{MODIS})\ *(EVI*LSWI*LST)]/\mathit{f}PAR_{MODIS}$

- log-transferred GPP_{MODIS} in the regression analysis because GPP_{tower} may reflect only a fraction, possibly a nonlinear relationship with GPP_{MODIS} which is an aggregate measure over the 8-day period

MODIS PSN/NPP algorithm: stage 1

- Basis is daily estimates of gross primary productivity, GPP - using MOD15 FPAR product
- For efficiency we need APAR – normally get fPAR from EO i.e. APAR = PAR * fPAR
- At-launch land-cover product ⇒ radiation conversion efficiency parameters from biome properties look-up table (BPLUT)

parameter	units	description
ε_{max}	(kgC MJ^{-1})	the maximum radiation conversion efficiency
$TMIN_{start}$	(°C)	the daily minimum temperature at which $\varepsilon = \varepsilon_{max}$ (for optimal VPD)
$TMIN_{full}$	(°C)	the daily minimum temperature at which $\varepsilon = 0.0$ (at any VPD)
VPD_{start}	(Pa)	the daylight average vapor pressure deficit at which $\varepsilon = \varepsilon_{max}$ (for optimal TMIN)
VPD_{full}	(Pa)	the daylight average vapor pressure deficit at which $\varepsilon = 0.0$ (at any TMIN)

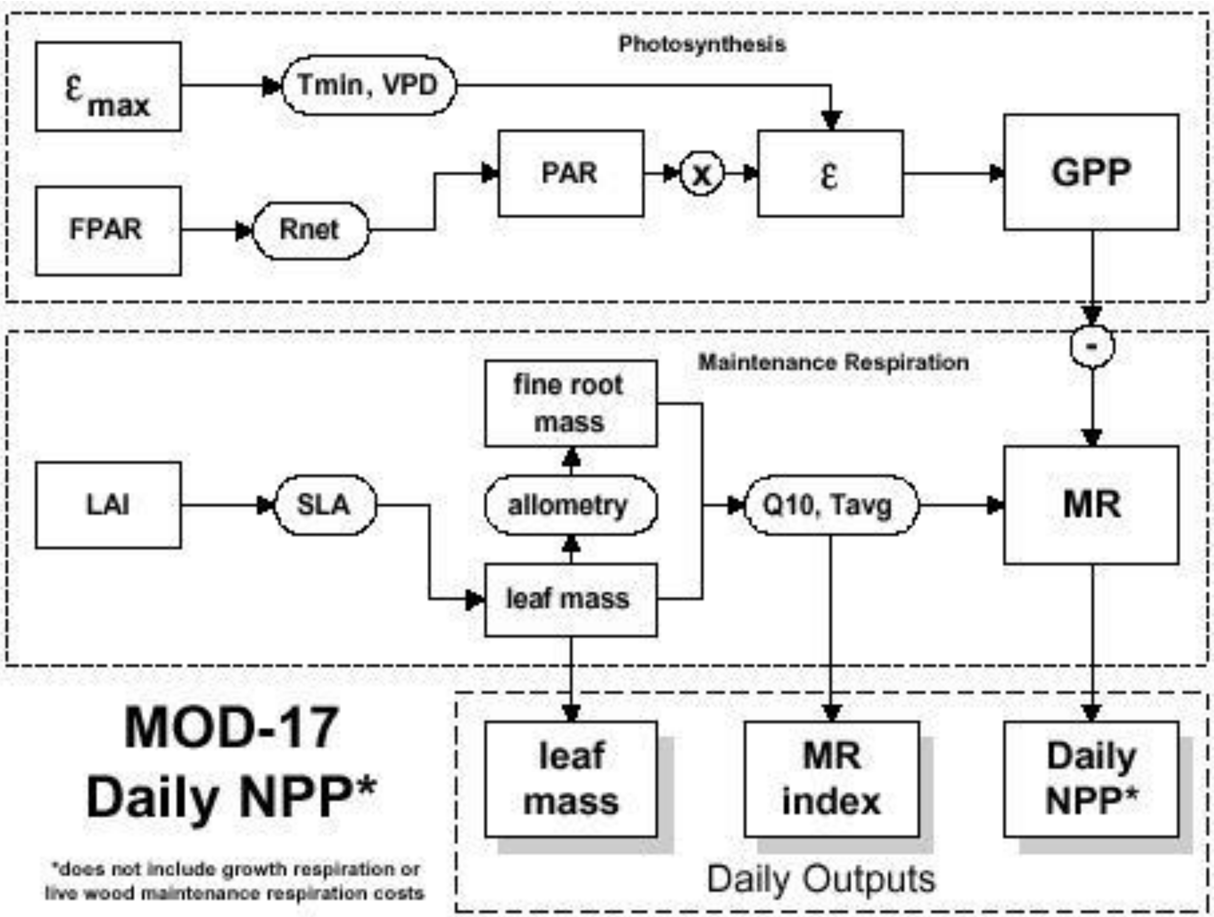
MODIS PSN/NPP algorithm: stage 1

- Parameters in table estimated by multivariate optimisation
  - minimise mean absolute error in daily GPP from MOD17 compared with separate Biome-BGC model.
  - This based on 1°x1° simulations using Biome-BGC model, met. data, 1km land cover product
    - Outputs include GPP, LAI and FPAR
  - Biome-BGC model
    - Predicts fluxes of water, carbon, nitrogen in a system including vegetation, litter, soil, and near-surface atmosphere.

MODIS PSN/NPP algorithm: stage 2

- Estimate (daily) maintenance respiration costs for leaves/fine roots
    - Exp. function of daily ave. air T, scaled by biomass of leaves and fine roots
    - Some processes no suited to daily time step (e.g. MR in woody veg., growth respiration) so empirical (based on annual averages etc.)
    - Output NPP is labelled NPP* to imply it is *estimated* NPP (can never be true NPP because of estimations based on varying time scales).
- Daily outputs
    - NPP*, leaf mass, index of daily MR

MODIS PSN/NPP algorithm

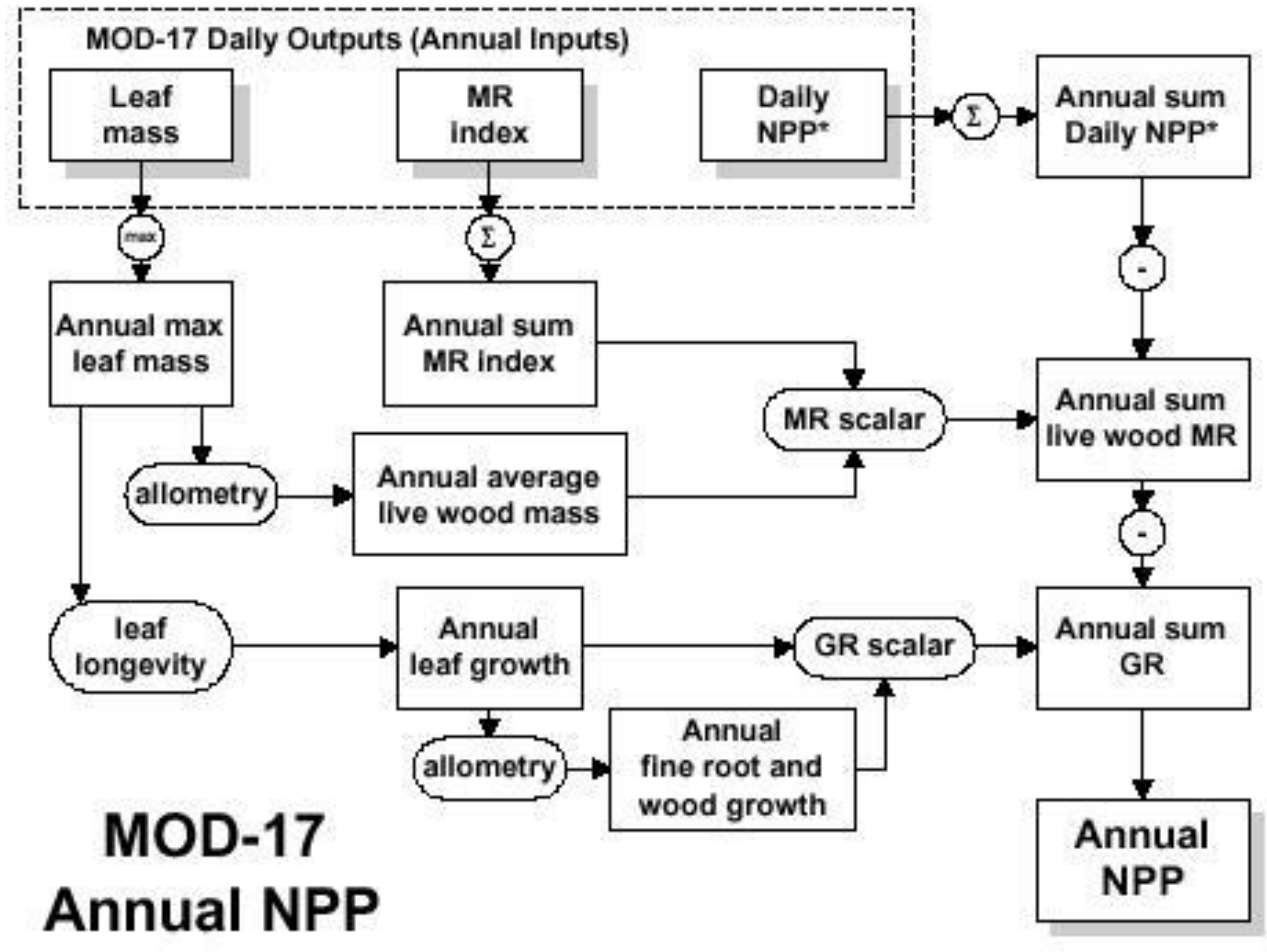


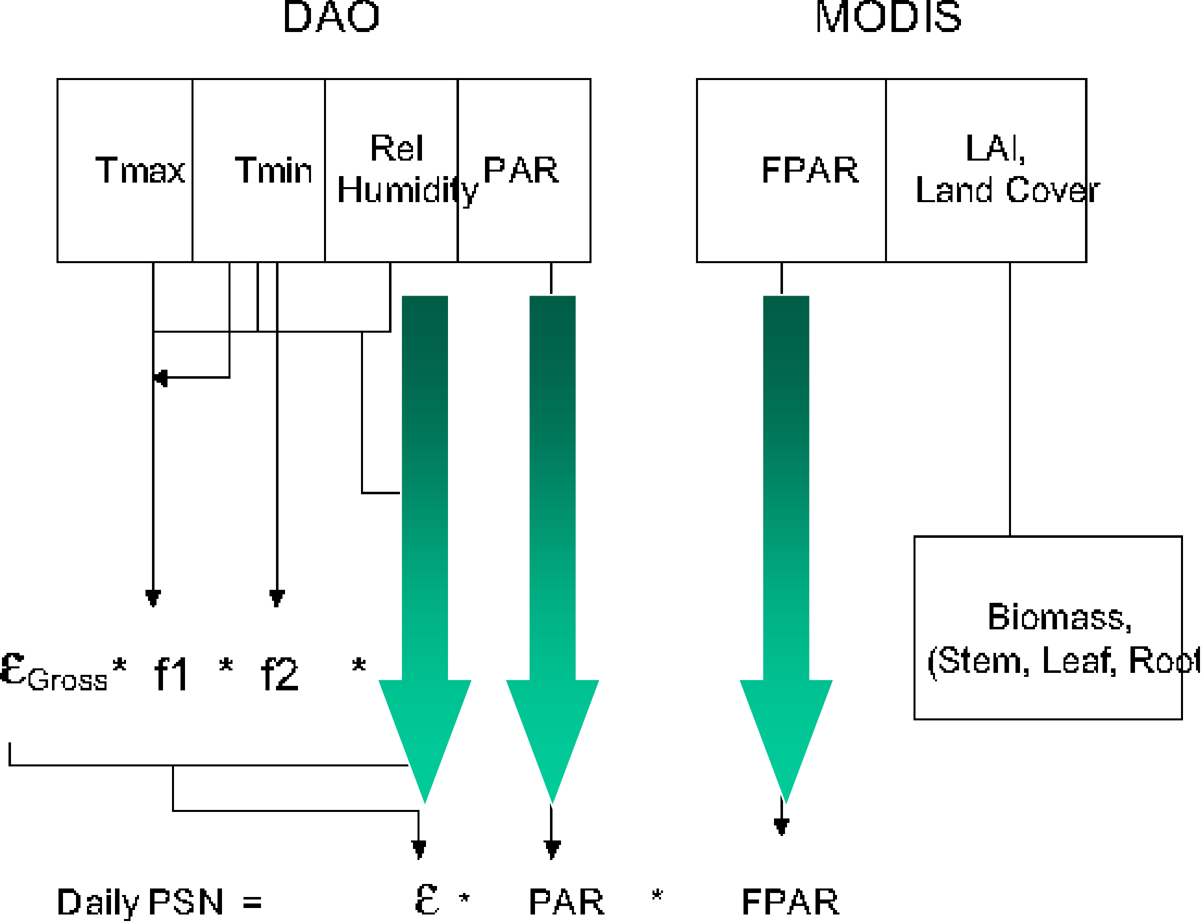
- Note inputs required for GPP assessment
- Then require LAI as well as other ancillary data to calc. MR – Maintenance Respiration

MODIS PSN/NPP algorithm: stage 3

- Annual algorithm
  - Estimate live woody tissue MR
  - Estimate growth respiration costs for leaves, fine roots & woody tissue
- Finally…..
  - Above are subtracted from accumulated daily NPP* to give estimated annual NPP

MODIS PSN/NPP algorithm





Daily Rm = f (Biomass, Tmax, Tmin)

Daily Rg = f (PSN, Rm)

Daily NPP = [PSN - Rm - Rg]

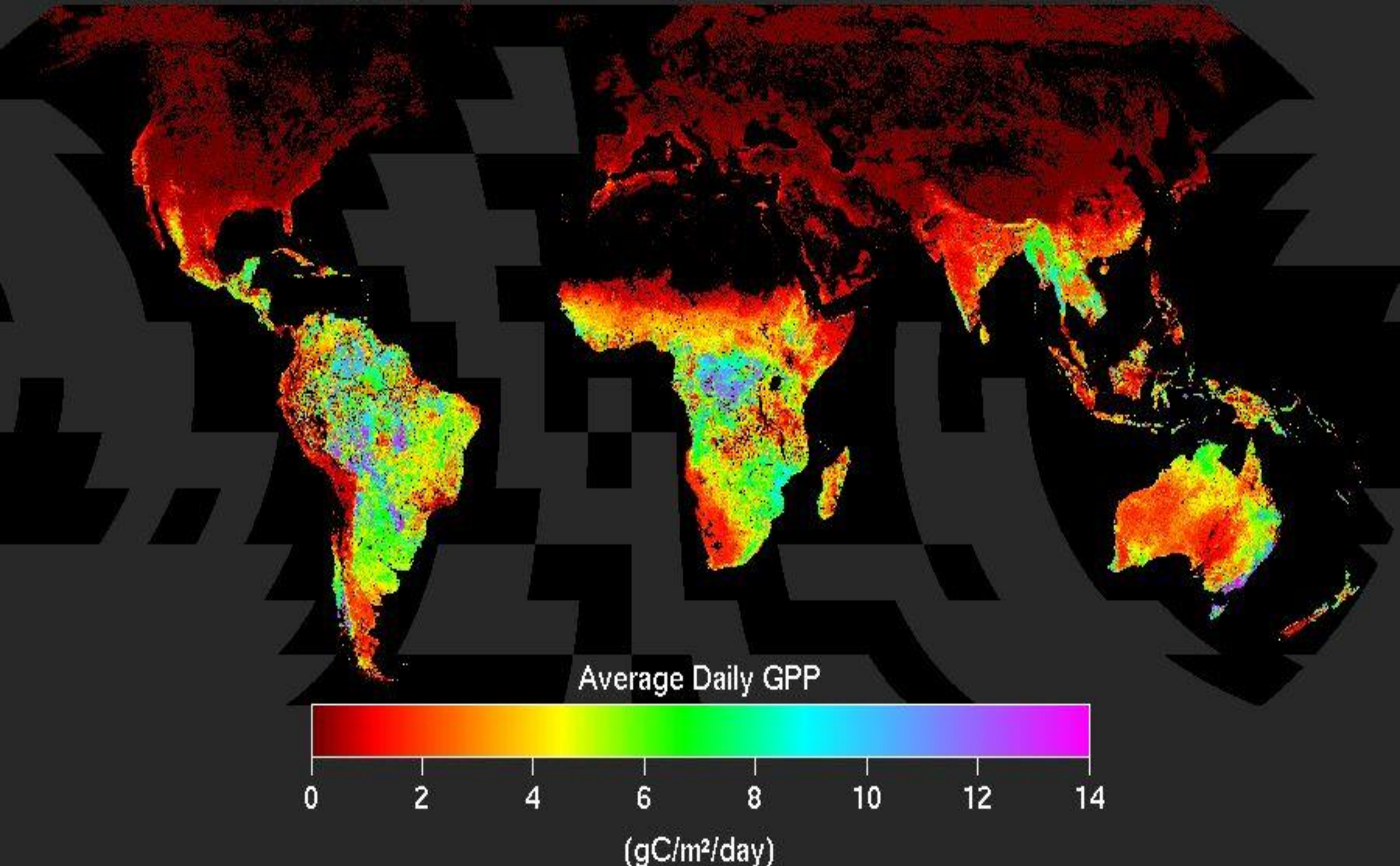
Annual NPP $= \int (NPP_{daily})$

- Overview
- DAO – Data Assimilation Office

is

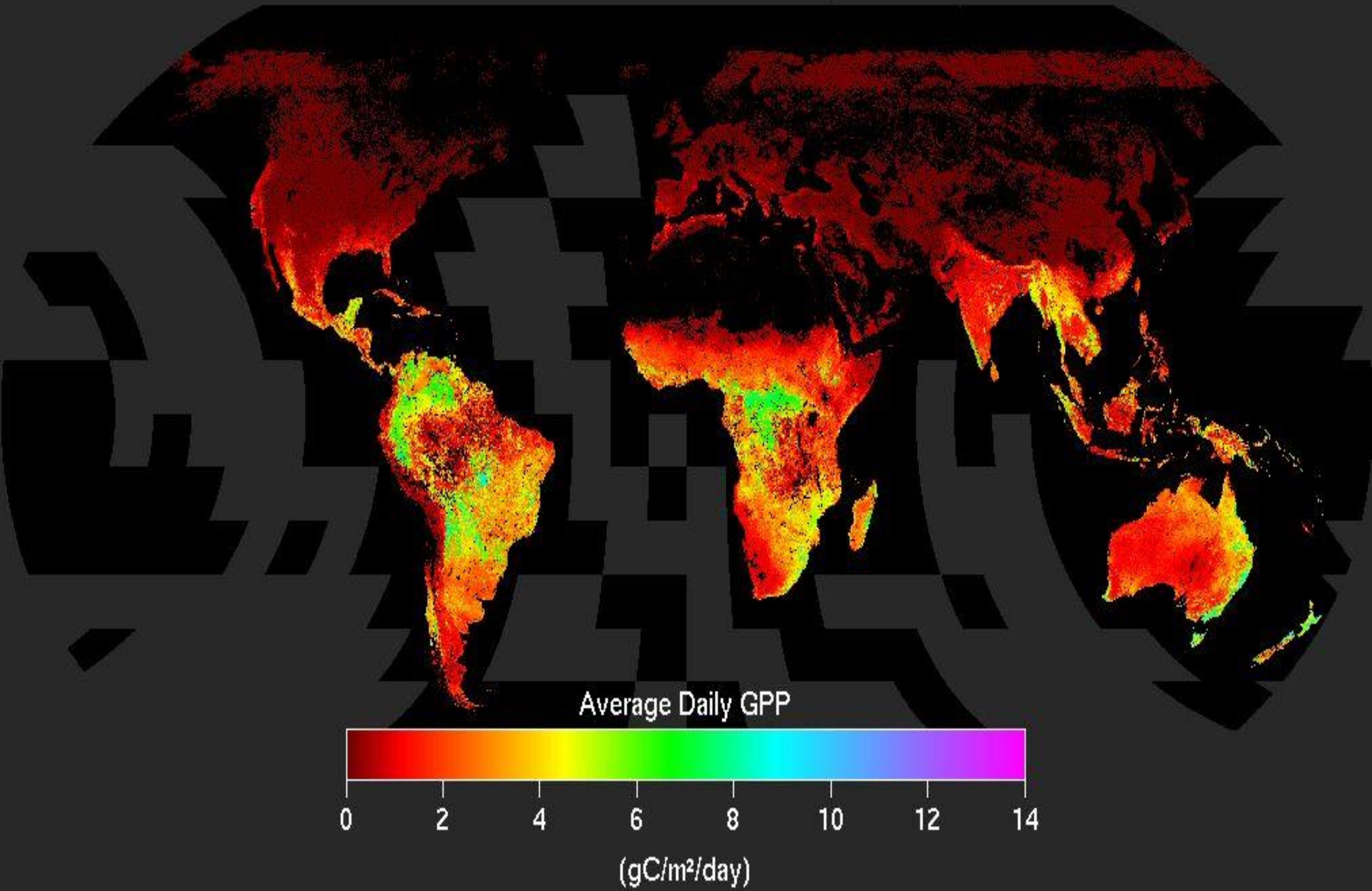
Gross primary production (GPP) from MODIS: Dec 26 – Dec 31, 2000

MODIS Land Science Team / University of Montana



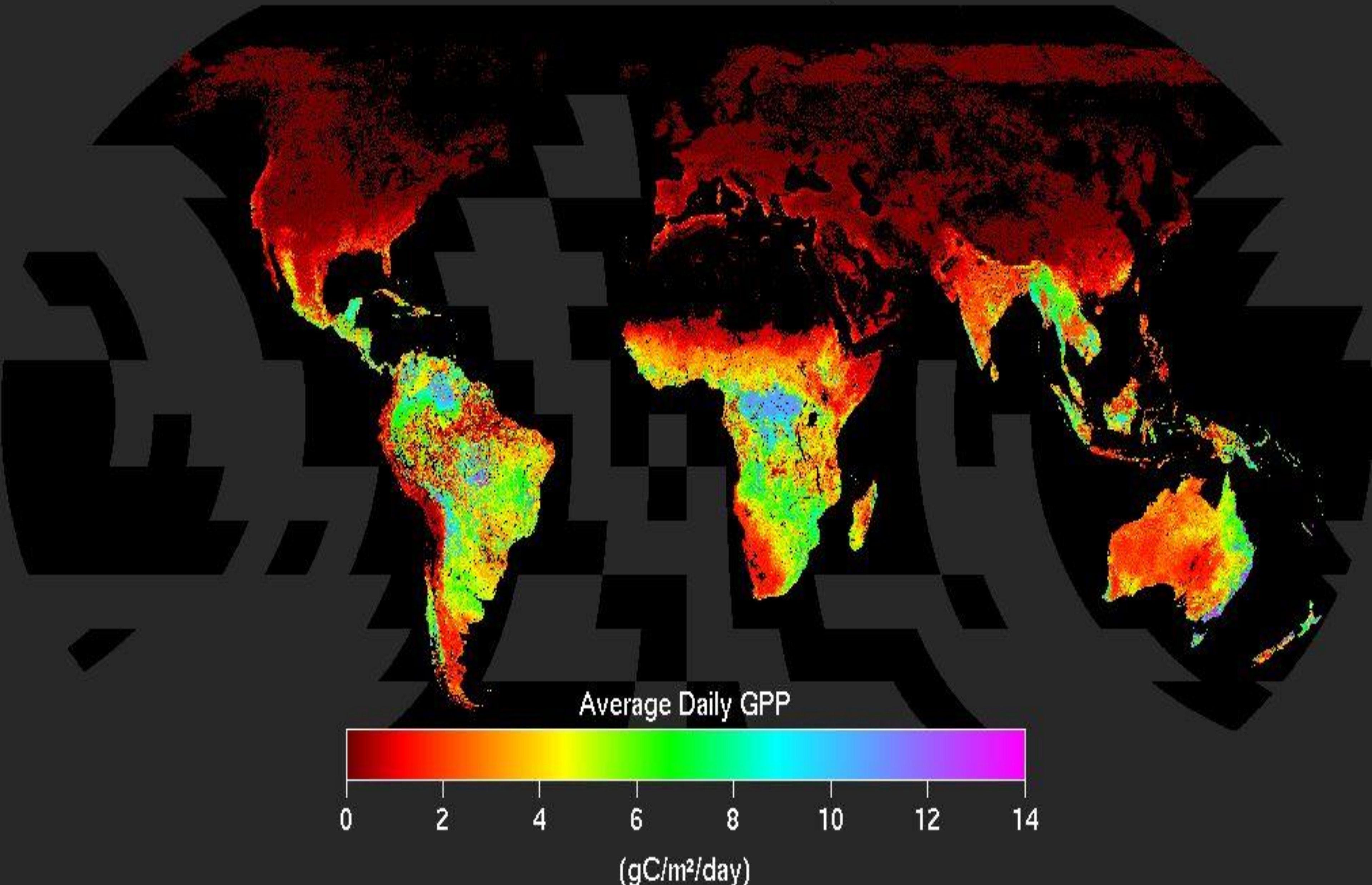
Gross primary production (GPP) from MODIS: Jan 1 – Jan 8, 2001

MODIS Land Science Team / University of Montana



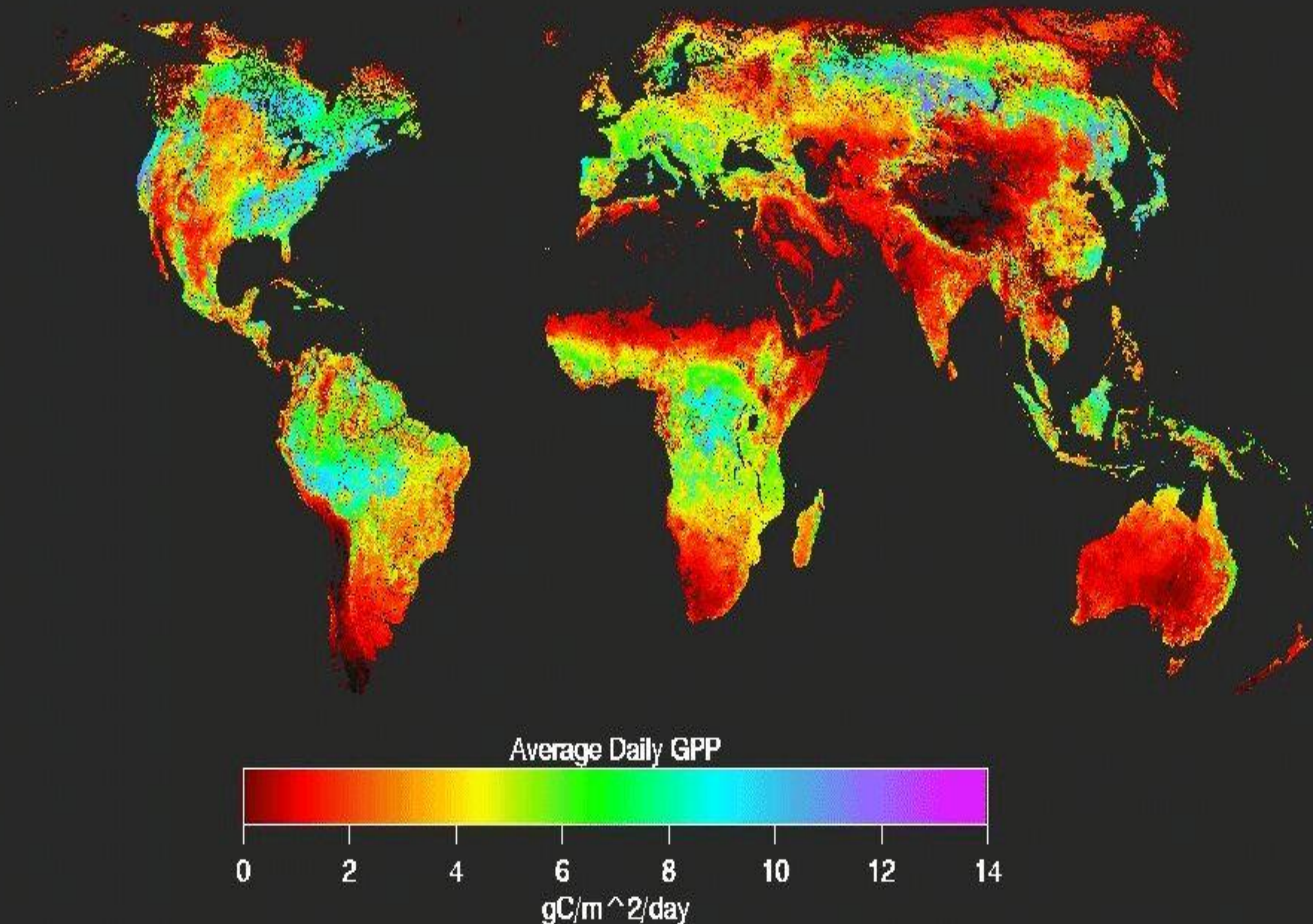
Gross primary production (GPP) from MODIS: Jan 9 – Jan 16, 2001

MODIS Land Science Team / University of Montana



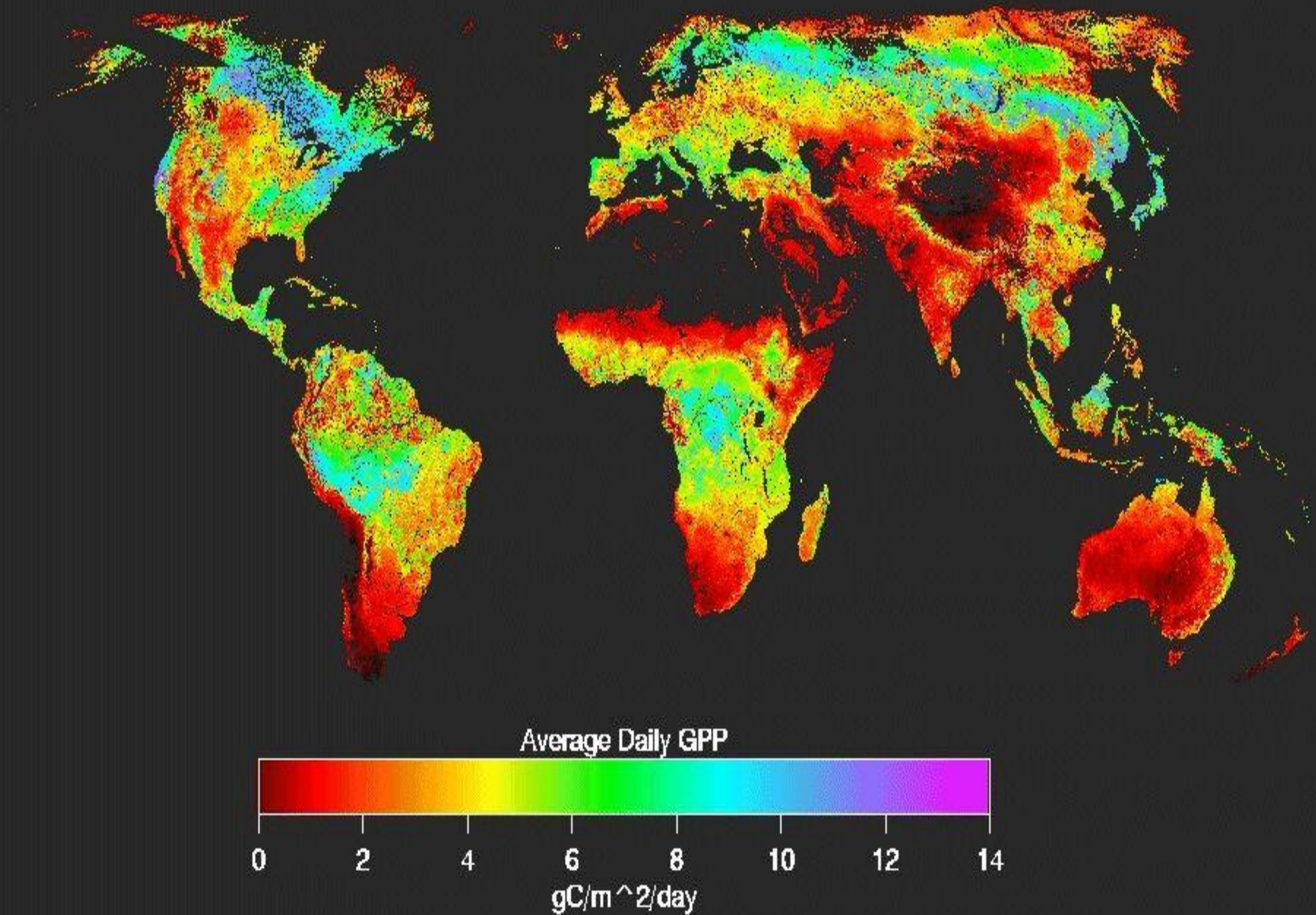
Gross Primary Production (GPP) 1km from MODIS: May 23 - May 30, 2001

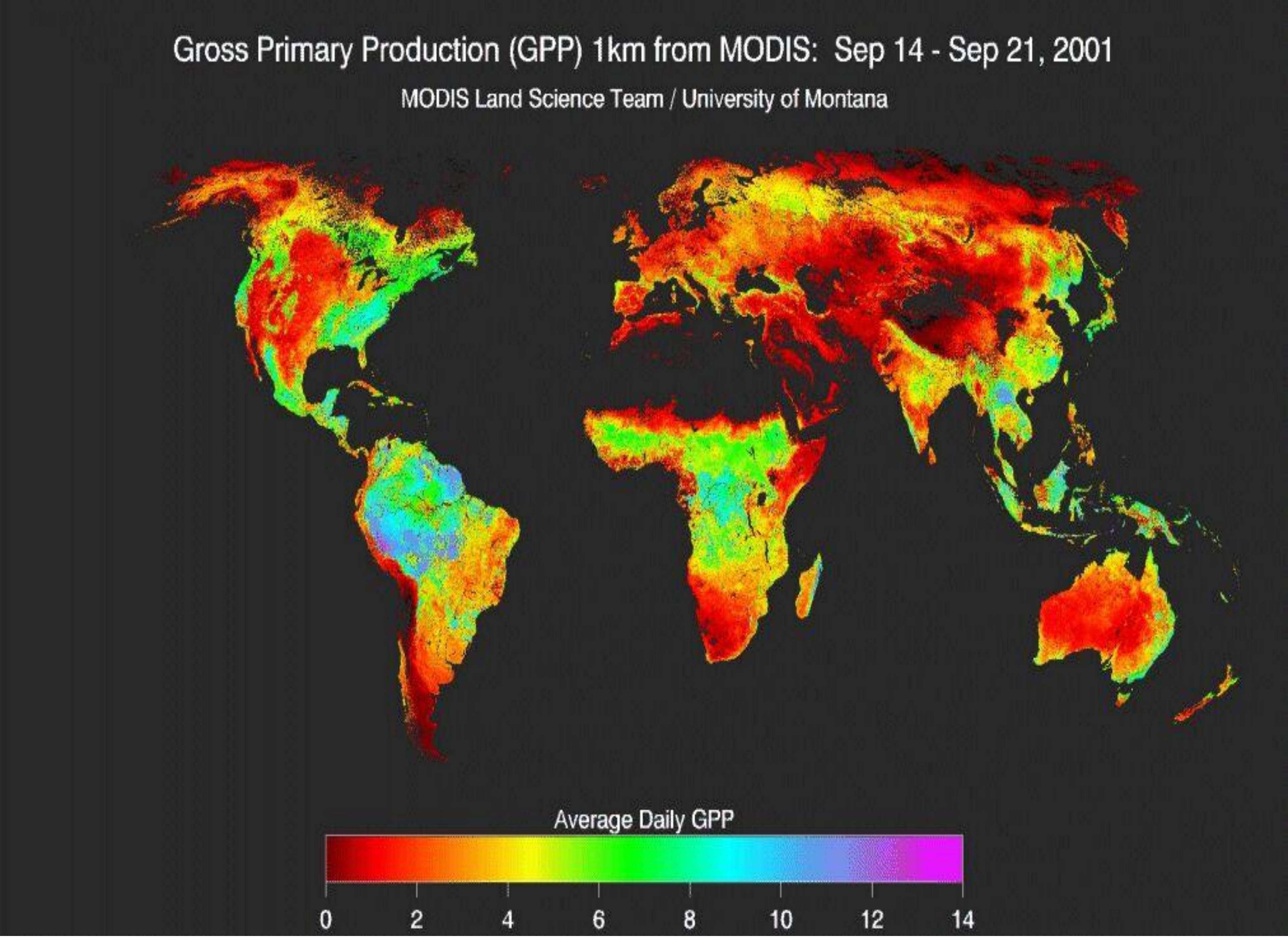
MODIS Land Science Team / University of Montana



Gross Primary Production (GPP) 1km from MODIS: May 31 - June 7, 2001

MODIS Land Science Team / University of Montana




Gross Primary Production (GPP) 1km from MODIS: Sep 14 - Sep 21, 2001
MODIS Land Science Team / University of Montana
Average Daily GPP
0
2
4
6
8
10
12
14

Algorithm design: issues

- Instrument issues:
  - spatial/spectral/temporal/angular resolution?
    - Moderate (100m to km) - heterogeneity?
    - High (<50m) – coverage?
  - Cloud clearing, atmos. correction?
- Implementation issues
  - Daily product?
    - Rapid, near real-time processing
      - Simple algorithm
  - Size (storage, transfer)?
  - Available ancillary data (PAR, LAI, NDVI, met. data etc.)

General algorithm design: BRDF/albedo

- Need samples of DHR and BHR
  - Need V. good registration and atmos. correction
    - directional effects easily masked
  - Sample BRDF, model to interp./extrap.
    - angular sampling crucial to accuracy
    - Principle plane (PP) and XPP….
  - Clouds reduce samples
  - Magnitude inversion if < 3 samples
    - Look-up veg. archetype BRDF from land-cover database
      - Same (ish) shape, difference only in magnitude
    - Associated error larger in this case
    - Interp. between black-sky and white-sky to get α
    - Integral of narrow bands to broadband

General algorithm design: PSN

- E.g. carbon budget studies
  - PSN requires daily GPP $\Rightarrow$ estimates of fAPAR ($\propto$ to NDVI) and ε_{max}
  - $\varepsilon_{max} = \varepsilon/f$ where f is a function of met. variables (temp., humidity) and LAI, to calculate MR.
  - PSN = Σ_{annual} daily NPP* - Σ_{annual} live wood MR – Σ_{annual} GR
  - 1km product (moderate resolution – heterogeneity?)
    - 8-day average of daily GPP (get rid of clouds)
    - reliance on LAI, NDVI (atmos. correction?)
    - Need meteorological information…..

Instrument considerations

- μwave/vis combined? e.g. ALOS, say (Japanese – launch 2003)
  - AVNIR-2 (Adv. Vis. NIR Radiometer)
    - 4 bands vis. NIR, 10m res. @ NADIR
    - +/- 44°, steerable (combine with PALSAR)
  - PALSAR (Phased array L-band SAR)
    - 10m res., 70 km swath
  - PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping)
    - For topo mapping but has angular signal (3 cameras)
- Combine to estimate land use, land cover, change….BUT maybe biomass? Carbon?

PSN/NPP links/references

- http://www.ipcc.ch/pub/tar/wg3/040.htm#810
- http://www.forestry.umt.edu/ntsg/RemoteSensing/netprimary/
- http://www.co2science.org/center.htm
- http://www.sciam.com/news/083101/2.html
- http://web.mit.edu/afs/athena.mit.edu/org/g/globalchange/www/rpt3.html
- ALOS: http://www.nasda.go.jp/Home/News/News-e/114eart.htm

- Dubayah, R. (1992) Estimating net solar radiation using Landsat Thematic Mapper and Digital Elevation data. Water resources Res., 28: 2469-2484.
- Monteith, J.L., (1972) Solar radiation and productivity in tropical ecosystems. J. Appl. Ecol, 9:747-766.
- Monteith, J.L., (1977). Climate and efficiency of crop production in Britain. Phil. Trans. Royal Soc. London, B 281:277-294.
- Running, S.W., Nemani, R., Glassy, J.M. (1996) MOD17 PSN/NPP Algorithm Theoretical Basis Document, NASA.
- Idso, K.E. and Idso, S.B. 1994. Plant responses to atmospheric CO2 enrichment in the face of environmental constraints: A review of the past 10 years' research, Agric. Forest Meteorol., 69:153-203.