



The MODIS NPP (Net Primary Productivity) Product – Concept, Definition and Validation

Arthur P. Cracknell

Emeritus Professor, University of Dundee

Abstract

One of the major components of the carbon cycle is the sequestration of carbon from CO₂ in the atmosphere at the surface of the Earth, land and sea. It is considerably more difficult to estimate the magnitude of this than to estimate the amount of carbon emitted by combustion processes and (possibly) by respiration.

This talk will comprise two components. The first will be a general tutorial presentation of the MODIS NPP product and the second will be concerned with reporting on two of our own research projects. This talk is only concerned with land surfaces, not the sea, so we are only covering part of the sequestration component of the carbon cycle.

We are very familiar with the use of the NDVI (Normalised Difference Vegetation Index) for studying land surfaces at continental or global scale; the ideas involved in the NDVI are very simple and the use of the NDVI is a major success story of satellite remote sensing. However, carbon sequestration is much more complicated because in this case we are trying to obtain quantitative values for biogeophysical parameters all over the land surface. The algorithm is not simple, as is evidenced by the fact that the relevant MODIS Algorithm Theoretical Basis Document (ATBD) for the Net Primary Productivity (NPP) product runs to 130 pages. I shall try to summarise this.

MODIS produces regularly on a global basis a value of NPP on a pixel by pixel basis with pixels approximately 1 km square over the global land surface and, of course, it has been validated with a number of test sites. However, these test sites are mostly in mid-latitudes and our interest is in the validation of the product for tropical areas, since the tropics are of major importance in carbon sequestration. Two research projects will be described, both of which are being carried out in conjunction with the Remote Sensing Department of Universiti Teknologi Malaysia (UTM). Both involve making the best estimate one can from in situ measurements of the quantities of vegetative material produced and thence the amount of carbon which has been sequestered, subtracting the loss by respiration. Given the pixel size of 1 km² it can be seen that this is not a trivial task. The first project is based on a test site within the Pasoh Forest Reserve in Negri Sembilan in the central part of peninsular Malaysia, preceded by some work on a Japanese test site. The Pasoh site consists of primary lowland mixed forest. This work is complete, but because the test site is so small, relative to the MODIS NPP pixel size, the results are limited to a very small number of pixels. Our second project is only in its very early stages, but is concerned with plantations where there is



the possibility of much larger areas of homogeneous vegetation so that we can match up with a much larger number of MODIS pixels.

1. Introduction

This is a mixture of, first, a general review or tutorial on GPP (gross primary productivity), NPP (net primary productivity), MODIS and the MODIS algorithms for these quantities and, secondly, a description of some project work on validation of the MODIS GPP and NPP products at test sites in Japan and (peninsular) Malaysia. This work involves collaboration between Dundee University and Universiti Teknologi Malaysia, UTM for short. This work is only concerned with land surfaces, not the sea, so we are only covering part of the sequestration component of the carbon cycle.

Global warming, and more generally climate change, is a topic of interest both to the environmental scientific community and to the general public. In any attempt at quantitative studies or modelling of climate change the carbon cycle is a central component. Quantifying the emissions of carbon dioxide to the atmosphere is difficult and quantifying the sequestration of carbon dioxide from the atmosphere at the surface of the Earth, land and sea is even more difficult.

Satellite remote sensing has the great advantage that it provides environmental information/data on a global basis and at frequent intervals. What it does not do, however, is to provide direct measurements of the quantities that we really want to measure. Let me give you a couple of examples:

- Sea surface temperatures
- Atmospheric profiles.

These are well-established cases where geophysical information is routinely generated from satellite data and these have been operational for a long time. In the case of sea surface temperature the data from the satellite consists of received radiance in the thermal infrared range of electromagnetic radiation (10-12 μm). We can use the raw data to study some oceanographic features such as circulation; for instance the Gulf Stream can be seen very clearly in thermal infrared images of the Atlantic Ocean.

But it is also possible to calculate the absolute value of the sea surface temperature if one needs to have it. The satellite-received infrared radiance is converted into sea surface temperatures via a physical model based on the Planck distribution function, the response functions of the filters/detectors and a method for atmospheric corrections. This is regularly done by receiving stations around the world using totally routine software. One use for these absolute values of the sea surface temperature is as input data to numerical weather forecast models or, when seasonally averaged, to climate models.

In the case of atmospheric profiles what one wants to obtain is the vertical distributions of pressure, temperature and humidity, but what the satellite system provides is the received radiances in a large number of spectral channels, mostly in various infrared and microwave wavelength bands/channels. The conversion of this data into the required profiles is achieved by using a model based on the radiative transfer equation; admittedly this equation involves various atmospheric parameters, the values of which are generally not available.

In both these cases the models used are based on physical processes which can be represented by mathematical equations and the implementation of the models involves quite large amounts of computing resources. In both the cases of sea surface temperature and atmospheric profiles the remote sensing gives frequent global coverage and validation is only possible at a small number of test sites.

When it comes to carbon sequestration then we need a model to relate the satellite-received data to what we want to know, namely the gross primary productivity (GPP) or the net primary productivity (NPP). The difference between these two quantities is that the GPP refers to the amount



of carbon removed from the atmosphere by the vegetation by photosynthesis, whereas the NPP is the GPP minus the amount of carbon returned to the atmosphere by the vegetation by respiration etc. NPP and the related PSN (photosynthesis) products are designed to provide an accurate, regular measure of the production activity or growth of terrestrial vegetation. These products have both theoretical and practical utility. The theoretical use is primarily for defining the seasonally dynamic terrestrial surface CO₂ balance for global carbon cycle studies such as answering the “missing sink question” of carbon. The spatial and seasonal dynamics of CO₂ flux are also of high interest in global climate modelling, because CO₂ is an important greenhouse gas.

The modelling goes back to the work of Monteith (1972, 1977). According to Monteith, the NPP of well-watered and fertilised annual crop plants is linearly related to the product of their light use efficiency, denoted by LUE or ϵ , and the amount of solar energy they absorbed, that is to the absorbed photosynthetically active radiation, APAR. APAR is commonly expressed as

$$\text{APAR} = (\text{fPAR}) \times (\text{PAR}) \quad (1)$$

where PAR is the incident photosynthetically active radiation and fPAR is the fraction of the photosynthetically active radiation that is absorbed by the canopy, i.e.

$$\text{fPAR} = \frac{\text{APAR}}{\text{PAR}} \quad (2)$$

APAR depends on the geographic and seasonal variability of day length and potential incident radiation, as modified by cloud cover and aerosols, and on the amount and geometry of displayed leaf material.

Monteith's idea could thus be represented by writing

$$\text{NPP} \propto \epsilon \times (\text{APAR}) \quad (3)$$

But, allowing for temperature and the availability of water, instead of using a simple constant of proportionality we use a function of temperature, T , and the waver vapour pressure deficit (VPD) which is commonly denoted by W . Therefore the relation (3) leads to:

$$\text{NPP} = f(T)g(W)\epsilon \times (\text{APAR}) \quad (4)$$

where $f(T)g(W)$ replaces the simple constant of proportionality and the functions $f(T)$ and $g(W)$ remain to be determined.

The practical utility of these PSN/NPP products is as a measure of crop yield, range forage and forest production, and other economically and socially significant products of vegetation growth. The value of an unbiased, regular source of crop, range and forest production estimates for global political and economic decision making is immense. These products will be available for all users worldwide. This daily computed PSN more correctly defines terrestrial CO₂ fluxes than simple NDVI correlations currently do to increase our understanding of how the seasonal fluxes of net photosynthesis are related



to seasonal variations of atmospheric CO₂. However, global GPP or NPP cannot be measured directly – you can only make a few isolated measurements at a few test sites.

The spatial variability of NPP over the globe is enormous; it varies from about 1000 gC m⁻² for evergreen tropical rain forests to less than 30 gC m⁻² for deserts. With increased atmospheric CO₂ and global climate change, and various human activities affecting the Earth's surface, NPP over large areas is almost certainly changing. Understanding regional variability in carbon cycle processes requires a dramatically more spatially detailed analysis of global land surface processes.

2. AVHRR

The first serious attempts to determine NPP from satellite data were based on the normalised difference vegetation index (NDVI) determined from the AVHRR. The NDVI is basically the difference between the reflectivity in the near infrared and the visible wavelength bands. Healthy young vegetation gives large values of the NDVI and old, senescent or diseased vegetation gives low values of the NDVI. And the NDVI has proved to be very useful in a number of contexts, predicting crop yields, studying diseased crops or forests, etc., etc. In addition to Monteith's idea that NPP or GPP is proportional to APAR, there was a second observation, namely that:

the NDVI is proportional to fPAR (Aswar *et al.* 1985)

and this was used as the basis of a method to calculate (global) NPP (Awaya *et al.* 2004). I think the point to make about this is to raise the question “how accurate is the AVHRR-derived NPP?”

I haven't seen any attempts to estimate the accuracy of the NDVI-derived NPP values. First, the relation given above is an empirical relation. And, of course, one should remember that the NDVI itself is just defined empirically to represent the health and/or abundance of vegetation. To expect to get an accurate value of a biophysical quantity out of such empirical relations, where no attempt is made to model the biological and physical processes involved, is naïve. Commonsense suggests that the general pattern of NDVI-derived NPP is along the right lines and the values of NPP are probably of the right order of magnitude, but beyond that

I don't want to go into the details of the use of AVHRR NDVI; it involves ways to estimate ϵ and functions like $f(T)$ and $g(W)$ to determine NPP. With the arrival of MODIS on the scene then attempts have been made to use a proper model for the biophysical processes involved. We shall now consider this.

3. MODIS

For many years satellite remote sensing was carried out with well-known systems, principally Landsat, AVHRR, SPOT, which have only a small number of spectral bands. What have been developed in recent years are hyperspectral scanners, or imaging spectrometers, basically the same kind of thing but with far more spectral bands. I want to say a little bit about MODIS and I guess if you want more information the source would be the NASA MODIS website which you can find easily enough with Google or some other search engine.

MODIS (short for Moderate Resolution Imaging Spectroradiometer) provides high radiometric sensitivity (12 bit) in 36 spectral bands ranging in wavelength from 0.4 μm to 14.4 μm . The wavelengths of the bands have been chosen to try to satisfy the needs of the user community. Two bands are imaged at a nominal resolution of 250 m at nadir, with five bands at 500 m, and the remaining 29 bands at 1 km. The instrument scans ± 55 degrees of nadir, i.e. like the AVHRR and much wider



than Landsat MSS, TM or SPOT for example. The altitude of the orbits of Terra and Aqua is 705 km so that MODIS scans a 2,330-km swath and provides global coverage every one to two days.

The first MODIS Flight Instrument, ProtoFlight Model or PFM, is flown on the Terra (EOS AM-1) spacecraft. Terra was successfully launched on 18 December 1999. The second MODIS flight instrument, Flight Model 1 or FM1, is flown on the Aqua (EOS PM-1) spacecraft; this was successfully launched on 4 May 2002. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days.

Many of the earlier satellite-flown instruments did not include on-board calibration facilities and this was a serious disadvantage when it comes to the quantitative use of the data rather than just producing images. MODIS includes four on-board calibrators as well as a view to space: a Solar Diffuser (SD), a v-groove Blackbody (BB), a Spectroradiometric calibration assembly (SRCA), and a Solar Diffuser Stability Monitor (SDSM).

A lot of work has gone into developing various different products for different categories of users. MODIS data are used to provide a whole heap of sets of information about various things; the data products.

Some of the products in this list can be generated by the application of algorithms which reflect basic fundamental equations of physics. The most notable of these is surface temperature. Following the launch of Terra, NASA started to produce regular global estimates of near-weekly photosynthesis and annual net primary production of the entire terrestrial Earth surface at 1 km spatial resolution, 150 million cells, each having PSN (photosynthesis) and NPP computed individually. MODIS has enough spectral channels to make estimates of NPP, but of course one needs an algorithm to determine the NPP. Unlike sea surface temperature, where there is a simple basic law of physics that relates the (surface-leaving) radiance to the required parameter (the sea surface temperature), there is no simple basic law of physics to determine NPP. One must have a model – it may take some account of the physical and biological processes involved but it will, almost inevitably, involve some empirical formulae and parameters. Although it has been clearly demonstrated that useful empirical relationships between measured NPP and measured APAR can be derived for individual sites or related groups of sites, the objective parameterization of these empirical relationships over the global range of climate and vegetation types is a more difficult problem.

We recall some of what we said when discussing AVHRR and let's start with GPP. Rather than using an empirical relation as was done with NDVI, namely that NDVI was proportional to fPAR, the algorithm that was developed with MODIS data is based on attempting to model more closely the actual biophysical processes involved in the sequestration of CO₂.

For a given type of vegetation under fixed conditions, time integrals of APAR have been shown to correlate well with observed NPP, but different relationships are observed for different vegetation types, and for the same vegetation type under different growth conditions. The amount of new growth that is produced from a given amount of APAR is a measure of the plant's RUE (radiation use efficiency), or radiation conversion efficiency, ϵ_{\max} . Early applications assumed a universal constant for radiation use efficiency (RUE), or ϵ_{\max} , that would apply across vegetation types, but later studies showed that this was unrealistic and that there are important differences in maximum efficiency between types. The RUE or ϵ_{\max} depends on the physiological characteristics of the plant, and also on the environmental conditions at any particular time. The challenge of estimating NPP from APAR over a global domain is in accounting for these multiple influences. It has been shown that differences in autotrophic respiration costs may account for some of the important differences in ϵ_{\max} between vegetation types, which suggests that APAR may be more closely related to the gross primary production (GPP) than to NPP (GPP is the photosynthetic gain before any plant respiration costs have been subtracted).



Consequently as far as modelling is concerned we work in two stages, First we replace NPP by GPP in equation (4) to give

$$\text{GPP} = f(T)g(W)\varepsilon \times (\text{APAR}) \quad (5)$$

Secondly, we determine NPP from GPP by taking “maintenance respiration” into account. This approach, using APAR to predict GPP instead of NPP, and later accounting for respiration costs through other relationships, has been employed in recent studies. Since the relationships of environmental variables, especially temperature, to the processes controlling GPP and those controlling autotrophic respiration have fundamentally different forms, it seems likely that the empirical parameterization of the influence of temperature on production efficiency would be more robust if the gross production and autotrophic respiration processes were separated. This is the approach that is employed in the MOD17 algorithm. (Running *et al.* 1999)

5. Algorithm overview

An overview of the MODIS NPP algorithm is shown in Figure 1. The uppermost box in Figure 1 is concerned with determining GPP and the middle box is concerned with determining the maintenance respiration and together they give the daily NPP in the bottom right-hand corner of the slide. To conform to this notation we rewrite equation (5) as

$$\text{GPP} = f(T)g(W)\varepsilon_{\max} \times (\text{PAR}) \times (\text{FPAR}) \quad (6)$$

where we have replaced ε by ε_{\max} to indicate that this is the intrinsic or maximum value of the radiation use efficiency (RUE) under the most favourable conditions of temperature and water availability and we have replaced APAR by $\text{PAR} \times \text{FPAR}$ just to relate more easily to Figure 1. The top line of the top box in Figure 1 is concerned with estimating $f(T)g(W)$ and the second line in the top box is concerned with determining PAR. For a given type of vegetation we take ε_{\max} and FPAR as constants and use them with the daily data to produce the daily GPP.

The starting point for the middle box in Figure 1 is the leaf area index, LAI, which comes from another MODIS product. There is another Algorithm Theoretical Basis Document (ATBD) for MOD-15 called “MODIS Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation Absorbed by Vegetation (FPAR) Product” and it is enormously long (130 pages) and complicated. I don’t have time (or energy) to go into the details of that.

The asterisk on the daily NPP* indicates that not all of the respiration terms have been included. I don’t have the time to go into all the details of how to get the annual NPP – I would just refer you to the Algorithm Technical Basis Document (ATBD) (Running *et al.* 1999). I should comment that the details of the algorithm involve a model, Biome-BGC which takes into account all sorts of processes, see Figure 2. (Biome = an area characterized by its flora, fauna, and climate, BGC = BioGeochemical Cycles.) The Biome-BGC model predicts the states and fluxes of water, carbon and nitrogen in a system including vegetation, litter, soil and the near-surface atmosphere. And that’s all I really want to say about it.

6. Validation



What I want to move on to now is some cooperative work between Dundee University and the Remote Sensing Department of Universiti Teknologi Malaysia (UTM) involving test sites in Japan and (peninsular) Malaysia. If you read the ATBD, the Algorithm Theoretical Basis Document, you will see that the Numerical Terradynamical Simulation Group of the College of Forestry at the University of Montana played a key role in the development of the MODIS NPP algorithm and its validation.

You might suppose that the obvious way to validate the MODIS NPP would be what we call the biometric method, i.e. people go out into the field and make measurements of the vegetation – in a forest for example by measuring the sizes of the trunks, branches, roots, leaves, litter as a function of time. However, generally speaking, validation is not carried out in this way. If you think about it the problems involved in doing this for the area corresponding to one pixel, i.e. 1 km x 1 km, is enormous and to have anything that is statistically significant you need to do this for a lot of pixels. What is widely used are eddy-covariance flux towers. First, these towers measure carbon and water fluxes and the surface energy budget, processes directly related to ecosystem function, continuously and semi-automatically, representing an area of 1-3 km². Secondly, there is a global set of over 80 such stations, fairly representative of a range of land surface types. Thirdly, the flux towers provide a network of organized personnel and equipment for making other comprehensive measurements, including ecophysiology, structure and biomass of the vegetation, fluxes of other greenhouse gases and micrometeorology. So what these towers are doing is measuring some of the quantities that are used within the various stages of the processing, rather than validating the final product. However, there are not many of these towers in tropical regions. The question, therefore arises as to how good is the MODIS NPP for tropical regions. I should just like to mention the work of one of the young members of staff at UTM who did her PhD in Australia using one of these flux towers and was able to show that there are some problems in using the MODIS NPP for savannah – which after all constitutes a large part of the land surface area of the globe (Kanniah *et al.* 2009)

7. Japanese test site

Our work is aimed at studying how valid the MODIS NPP product is for tropical forests. And we are actually trying to use the biometric method.

Biometric measurements using the summation method, also known as the classical method (i.e. ground data), to estimate NPP have been used successfully in Japan since the 1960s. This method measures individual tree biomass directly on the ground by measuring all the individual components and calculating the growth increment. Parameters such as weight of stem (W_s), weight of branches (W_b) and weight of leaves (W_L) were used in this calculation. Summation of growth increment in these quantities, along with litter production and grazed amount, then are utilized to estimate NPP in this approach. We have used MOD-17 to obtain satellite-derived NPP for 2004, 2005 and 2006 for a study site and compared this with the in situ results available for this site.

This study was conducted on a Japanese experimental plot, for which the annual NPP was already published by Komiyama *et al.*, (2007). This experimental plot is located in central Japan (36° 06' N, 137 ° 04' E, 1,000 m a.s.l), Takayama City, Gifu Prefecture, Japan and is covered by 110-year-old temperate deciduous trees. The total area of this experimental plot is about 1.06 ha. [The dominant overstory species for this forest are *Quercus mongolica* var. *grosseserrata*, *Acer palmatum* subsp. and *Castanea crenata*. From 2004 to 2006, the mean annual temperature and the annual precipitation ranged from 7.1 to 8.1°C and 2357 to 3310 mm, respectively.] Three years of level 1B Terra MODIS satellite data (2004, 2005 and 2006) for the experimental plot have been acquired from <http://ladsweb.nascom.nasa.gov>. Minimum cloud cover of MODIS satellite data and a date towards the end of the growing season have been chosen using quick-look command provided in this free download website. Thus, the three dates of MODIS satellite data we have used are: i) 17th Oct. 2006; ii) 12th



Sept. 2005 and iii) 29th Oct. 2004. Three years annual NPP MODIS products for the Japanese experimental plot identified above have been produced in this study. The conversion of units from $\text{g m}^{-2} \text{ yr}^{-1}$ to $\text{t ha}^{-1} \text{ yr}^{-1}$ has been applied to enable comparison of results between the MODIS data and the field data. These results have already been published (Rasib *et al.* 2007), see Table 1.

The value of the MODIS NPP and the in situ data show that the magnitudes of the values and the variations from year to year of the annual NPP from 2004 to 2006 from the satellite data and the field observations are comparable. The pattern is the same, with the maximum value of annual NPP for the year 2006 and the minimum value for the year 2005. The results showed that, the trend of the annual NPP obtained using both measurements are comparable; however there are differences in values. These differences were used to calculate Root Mean Square Errors (RMSE) and the result is $0.8 \text{ t ha}^{-1} \text{ yr}^{-1}$.

The results are generally encouraging. For instance the annual NPP result from this study is consistent with results from the previous research as reviewed by Kira (1977); the range of above-ground NPP of cool temperate deciduous broad leaved forest in Japan was given as 3.47 to $8.74 \text{ t ha}^{-1} \text{ yr}^{-1}$ using summation methods. However, there is still a lot to be done. Our study area is quite small (1.06 ha) compared with the IFOV (1 km square, = 10^4 ha) and the satellite-derived value is an average over the whole IFOV. In moving on to test sites in peninsular Malaysia we shall be considering larger field/test sites. Also, of course, our interest is in tropical forests but the Japanese study site is just over 35° north of the equator. We therefore await with interest the results that we hope to obtain from our tropical forest study areas in Peninsular Malaysia.

8. The Pasoh study site in peninsular Malaysia

Our second study area is in Pasoh Forest Reserve which is located in Negeri Sembilan in the central part of Peninsular Malaysia. The study area is situated between latitude $2^\circ 59' \text{N}$ and longitude $102^\circ 19' \text{E}$ and its topography lies between 11 m to 21 m above sea level. It is located about 8 km from the town of Simpang Pertang, approximately 70 km southeast of Kuala Lumpur (140 km by road). With an area of 2,450 ha, the Pasoh Forest Reserve is surrounded on three sides by oil palm plantations and joined to virgin hill dipterocarp forest on its northeastern boundary. The main part of the reserve consists of lowland dipterocarp forest of the Keruing-Meranti type, with a core area of about 600 ha of undisturbed forest surrounded by a buffer zone of regenerating logged lowland forest.

The continuous canopy height is approximately 35m, although some emergent trees exceed 45m. Pasoh Forest Reserve generally receives relatively high annual rainfall ranging from 1728 to 3112 mm (mean 2054 mm), which is relatively low for Malaysia, but the fairly even distribution of rain throughout the year permits the development of typical lowland rain forest. The highest precipitation normally occurs during the months of March to May and September to January. Meanwhile, the mean monthly temperature is in the range from 24.5°C to 27°C . This Forest Reserve contains three plots that have been used extensively for studying primary productivity of tropical rainforest during the International Biological Program (IBP) since 1978. Currently there are still some on-going joint research projects between the Forest Research Institute Malaysia (FRIM) and foreign research workers from the National Institute for Environmental Studies, Japan — NIES.

For the purpose of this study, level 1B of morning Terra MODIS satellite data for Peninsular Malaysia was used, and this data has been acquired from <http://ladsweb.nascom.nasa.gov>. MODIS satellite data dated 18 May 2004 with minimum cloud cover has been selected using the quick-look menu provided in this free download website. For the local scale NPP mapping purposes, this data has to be geocoded to the Malaysian Rectified Skew Orthomorphic (MRSO) projection coordinate system. The results will be presented. They show an estimated annual NPP for Peninsular Malaysia and Pasoh Forest Reserve in 2004. The annual NPP value for Peninsular Malaysia and Pasoh Forest Reserve are in the range of from 0 to $804.37 \text{ gC m}^{-2} \text{ yr}^{-1}$ and 0 to $633.85 \text{ gC m}^{-2} \text{ yr}^{-1}$, respectively. We are still, just now, awaiting the results of field data for the Pasoh Forest Reserve to compare with these calculated values. The PhD student involved is still working on this.



9. The future

We are now turning our attention to oil palm estates in cooperation with the Malaysian Palm Oil Board. Why are we interested in Oil Palm estates? There are two reasons: (1) although we have been able to make comparisons between MODIS NPP and biometric data the results are scarcely of any statistical significance because of the minute number of pixels involved and (2) there are mixtures of species of trees which are irregularly arranged on the ground and are at different stages of growth. It seemed to us that oil palm plantations in Malaysia provide an excellent opportunity to provide a very large test site for testing the validity of MODIS derived estimates of tropical NPP. There are two reasons for this. As already indicated above, in a mixed forest, trying to collect data on biomass production over anything like the size of one pixel (1 km by 1 km) is more or less impossible. And even one pixel is not enough, for a whole variety of reasons, such as edge effects, overlap of fields of view, technical limitations of the instrument such as point spread functions, etc. Thus oil palm estates (and to a much lesser extent rubber plantations) are almost as good as one might design if one were starting from scratch to make test sites. Key characteristics typically include:

- (a) large area, comparable with the size of as pixel or possibly even several pixels.
- (b) single species
- (c) all trees at the same stage of growth on an estate
- (d) trees planted on a regular pattern; this is a two-dimensional triangular grid with a grid spacing of 10 m.
- (e) different estates with trees at different stages of development; this gives us the multi-temporal aspect.

By determining the (total above ground) biomass of a single oil palm tree it should be possible to estimate the biomass for a whole estate (assuming there is little variation in tree growth across a single estate). Ideally, such a validation exercise as this requires a time series of 3-5 years, or even longer; but one doesn't have this sort of time. However, this could be simulated with different estates (of the same species and preferably on the same type of soil, slope, etc., etc.) with trees of different ages and estimate the annual GPP or NPP (as a function of age of the trees) by differences between the biomasses of estates of different ages for comparison with the satellites' output.

Areas of oil palm estates (and their ages) could be identified through a mixture of land use maps, high spatial resolution remotely sensed data and MPOB records.



9.1 DMCii

For this project we responded to an AO from DMCii and our proposal was accepted. Thus we are planning to use DMC data to classify scenes of peninsular Malaysia in conjunction with land use maps and MPOB records, to identify oil palm estates and, hopefully, to identify the ages of the trees in each estate. We think DMC is a wonderful system, giving Landsat MSS spectral resolution with TM spatial resolution and AVHRR frequency of coverage. We also think that the DMC system is less well known in the remote sensing community than it deserves to be.

10. Conclusion

We have a long way to go but our objective is to see how good the MODIS NPP algorithm is for tropical forests and, if necessary, to see how the algorithm can be improved.

Acknowledgements

I would like to acknowledge the involvement in this project of Dr Mark Cutler, University of Dundee, and the following colleagues from the Remote Sensing Department, Universiti Teknologi Malaysia: Prof. Ab Latif Ibrahim, Prof. Ibrahim Busu, Dr Kasturi Kanniah, Miss Jia Huan Tan and Mr Abd Wahid Rasib.

References

- Asrar, G., Kanemasu, E.T., Jackson, R.D., and Pinter P.J., 1985. Estimation of total above-ground phytomass production using remotely sensed data, *Remote Sensing of Environment*, **17**, 211-220.
- Awaya, Y., Kodani, E., Tanaka, K., Liu J., Zhuang, D. and Meng Y., 2004. Estimation of global net primary productivity using NOAA *images* and meteorological data: changes between 1988 and 1993, *International Journal of Remote Sensing*, **25**, 1597-1613.
- Kanniah, K.D., Beringer, J., Hutley, L.B., Tapper, N.J. and Zhu, X., 2009. Evaluation of collections 4 and 5 of the MODIS Gross Primary Productivity product and algorithm improvement at a tropical savanna site in Northern Australia, *Remote Sensing of Environment*, **113**, 1808-1822.
- Kira, T. (1977). Primary productivity of Japanese Forests. Edited by Shidei, T. and Kira, T., Japanese Committee for the International Biology Programme. University of Tokyo Press. (16). pp: 1-9.
- Komiyama, A., Abd.Wahid bin Rasib, Kato, S., Takeuchi, T., Nagano, I. and Ito, E. (2007). Net primary production of a 110-year-old deciduous hardwood forest. Proceedings of 21st Century Centre of Excellence Programme on "Satellite Ecology", Gifu University, Gifu Prefecture, Japan. 27th Feb. pp: 1112-1118.
- Monteith, J.L., 1972. Solar radiation and productivity in tropical ecosystems, *Journal of Applied Ecology*, **9**, 747-766.
- Monteith, J.L., 1977. Climate and efficiency of crop production in Britain, *Philosophical transactions of the Royal Society of London*, Ser. B, **281**, 277-294
- Rasib, A.W., Ibrahim, A.L., Cracknell, A.P. and Paidi, M.A. Evaluation of the MODIS NPP product for a Japanese test site. Proceedings of the RSPSoc Annual conference, Newcastle-upon-Tyne, September 2007 (RSPSoc, Nottingham).
- Running, S.W., Nemani, R., Glassy, J.M. and Thornton, P.E., 1999. MODIS daily photosynthesis (PSN) and annual net primary production (NPP) product (MOD17). Algorithm Theoretical Basis Document version 3.0. *Source MODIS website*.



Figures

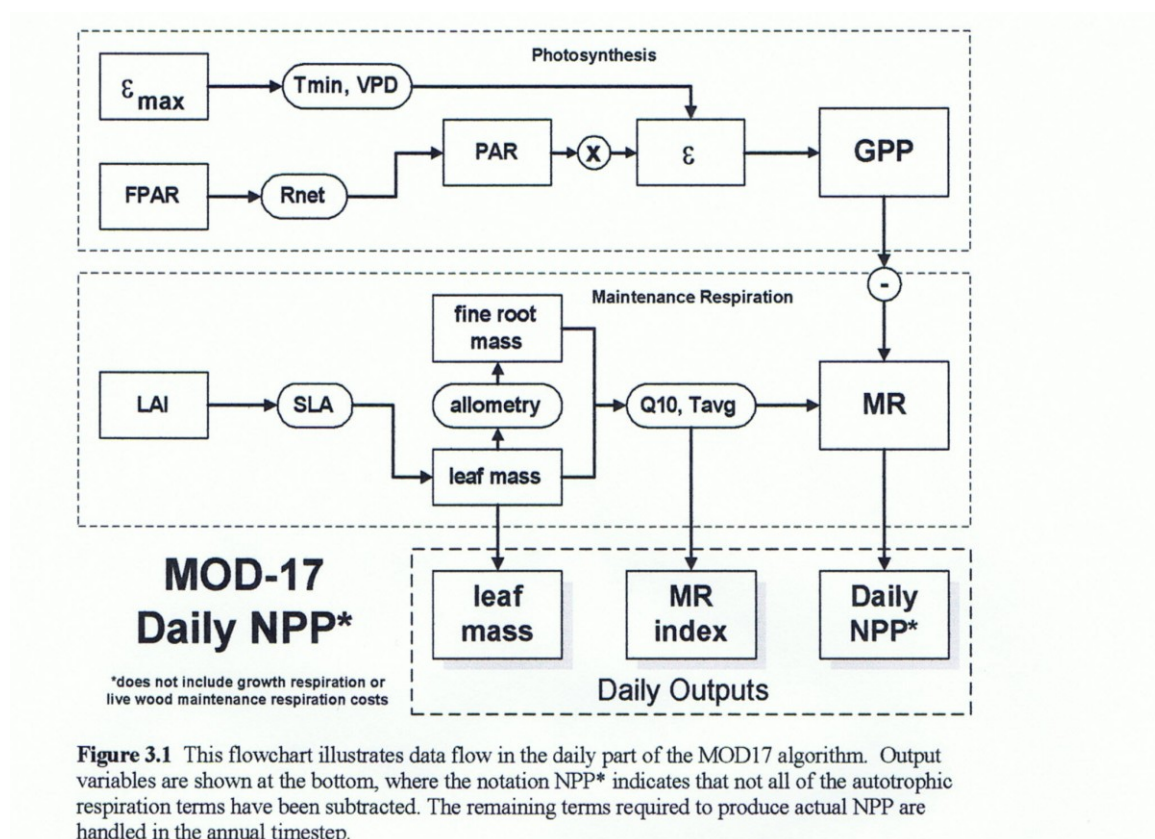


Figure 1. MODIS NPP algorithm (Running et al. 1999).

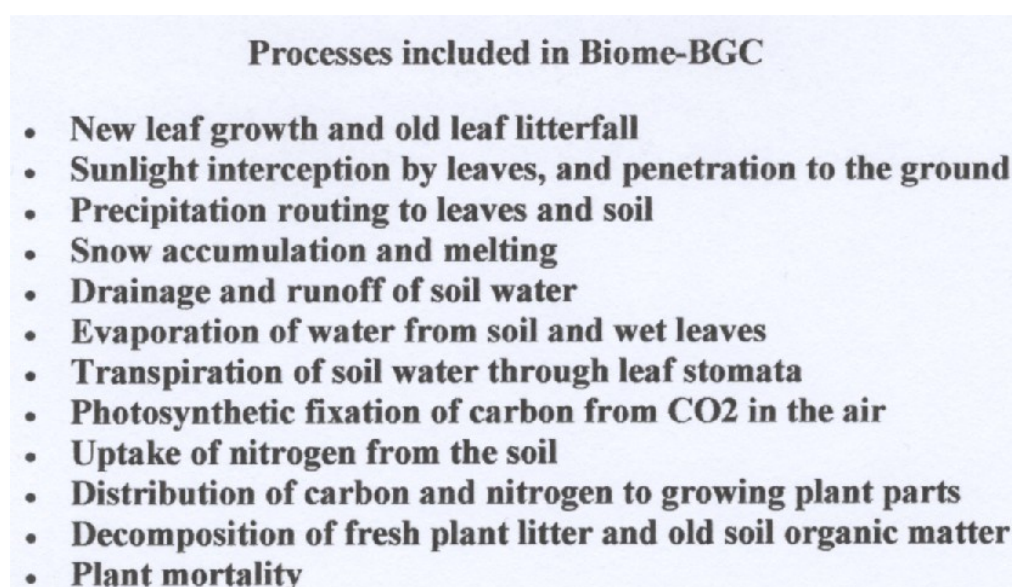


Figure 2. Processes included in Biome-BGC (Running et al. 1999).



Table 1.

NPP value in the experimental plot.

Year	MODIS	MODIS	Field data
	(g m⁻² yr⁻¹)	(t ha⁻¹yr⁻¹)	(t ha⁻¹yr⁻¹)
2004	1301.4	6.5	5.2
2005	444.9	2.2	2.8
2006	1492.6	7.5	7.5