Field assessment and estimation of light under various canopy conditions and in gaps

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My interest in the light regime in vegetation is largely driven by my background in remote sensing. For those of you who are not *au fait* with remote sensing, it means I am interested in the signals left over after the vegetation has done its bit and absorbed whatever it is going to use. Some of that light is reflected back and is then available for measurement from above the canopy, by camera or other sensors from helicopter, aircraft and from satellites. I try to understand and exploit the signals that we can measure, from satellites in particular, to get regional and global views of ground cover such as forests and crop canopies, and then make very broad measurements that will tell us about structure, function and dynamics of the vegetation. So I am looking at what is left over after radiation has been intercepted by vegetation, and using it to understand what is going on in the bit that is absorbed.

We have got expert forestry people here, so does anyone recognise the forest in the photo above? *(audience laugh)* This is the antithesis of the continuous cover forest, but it is an example of one of the areas I have worked in. From my point of view,
this is a very easy model to work with because the trees are all similar. When you are working from satellites where you have a pixel covering hundreds of metres, it makes life a lot easier (and more boring!) if you can make the assumption that the area covered by a pixel is broadly uniform. Of course, we know that it is not the case in the real world where there is huge heterogeneity across all scales.

I shall be talking about how we try to understand the interaction between radiation and vegetation, I'll explain a little bit about how we go about measuring the light regime, which is difficult, and about the simulation and modelling methods, and new tools that are available for measuring and probing the light regime, and I shall also discuss some of the applications of this modelling.

One of the key interests in the forest light environment is the state of the forest from a climate and a carbon point of view. How much biomass is there, and what happens when you change the management regime or if it is disturbed either deliberately, or through fire, insect infestation, and other natural causes? Also, what is the rate of accumulation of carbon in forest stands and how efficient are they? What are their responses to changes in climate and management? There is also, of course, commercial interest in these issues in terms of yields and rates and rotation strategies etc.

The problem with remote sensing measurements is that you can’t normally go down and make direct measurements, so you are always having to infer what you can from the signal you are receiving. It doesn’t measure dbh or stem density or even the tree canopy height, or very rarely. So we have to be aware of the assumptions and inferences we need to make.

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**Context: direct/diffuse light**

**Light environment?**
- Plant growth optimises canopy structure to maximise diffuse interception
- > 25% increase


*Fig. 2*
The direct/diffuse ratio is important and Maurizio has already discussed it in some detail. For example, forest canopies in northern temperate boreal regions are often optimised to operate in a diffuse light regime and grow to maximise the amount of diffuse radiation. If you remove material from the canopy and then return several years later the canopy will have grown to optimise the amount of diffuse radiation available. Fig. 2 shows work done 10 to 15 years ago and material returning to the same point over time. This was a field based study where they went out and removed some material, then revisited the same spot at intervals to measure how much diffuse radiation there was and it shows the increased branching in the tree area.

**Context: direct/diffuse light**

- Light environment?
  - Can increase efficiency by 5 - > 100% (crops)
  - Significant globally?

![Graphs and data](image)

Alton et al. (2007) GCB, 13. 776-787

**Fig. 3**

The study above (Fig 3) is looking at various canopy types which are shown in the different panels (there are crop and forest types here) and the efficiency of their gross production, i.e. the amount of photosynthesis going on for a given plant type as a function of the PAR (photosynthetically active radiation) available. In each case there are two curves, one where the fraction of the diffuse light is less than 50%, shown by the light circles, and one where it is greater than 50%. In all cases you
have got the same increase and then levelling off that Murizio noted, but it also shows that where you have got a higher proportion of diffuse radiation you have got more efficient photosynthesis going on. So this reinforces the importance of the quality of light in terms of diffuse versus direct. Plants grow in all sorts of environments, and very rarely in isolation, so many are optimised to be efficient at dealing with diffuse radiation.

If you are interested in the light levels themselves, or the things which change them, such as leaf area of the canopy, you can use indirect measurements which infer the amount of light available or conversely the amount of light which is intercepted as a function of leaf area and height and so on. There is a range of tools and methods that have been around for a long time and essentially measure how much light gets to the bottom of the canopy, or to a particular level of the canopy relative to how much is arriving at the top. But they make various assumptions in the process and we have to know a little bit about these assumptions as some of them perhaps hold better than others, or hold better under certain conditions than others, and the assumptions that are made may not be met in practice, so may create distortions that we have to bear in mind.

Leaf area index (LAI) is essentially a number that tells you how much leaf area there is in a unit area of canopy per unit ground area, or m² of leaf per m² of ground, so it is a dimensionless number. For example, if you have got a number that is 0.5 there would be 0.5m² of leaf area over 1m² of ground, which is a low LAI canopy. In a deciduous forest you may get up to between 5 and 10, and in a tropical forest you may get up to 20. You might wonder what it has to do with the light environment, but of course the LAI is what modifies the light environment within a canopy. The amount of leaf area you have per unit height and per unit area is what is available within a canopy to absorb radiation. The amount of leaf area you have got and how it is distributed within the canopy essentially determines what is left at the bottom and what is left within each layer of the canopy. So one of the ways we characterise both canopy productivity and the light regime is through relationships with leaf area.

There are a number of different ways you can measure leaf area. Delta T Instruments are here with their Sunscan system, and there are other variants of the same idea. Essentially you have a sensor of some sort, you have a measurement which is above or outside the canopy and gives the amount of radiation arriving, then you have a measurement underneath the canopy which gives the amount of radiation reaching the bottom or the different levels within the canopy, and the one relative to the other tells you how much is being intercepted. You make some assumptions about how the leaf area is arranged within the canopy, and it tells you about the leaf area in the canopy.

One of the commonest and most useful ways of doing it these days is by using hemispherical photography, simply because you can use off-the-shelf cameras and lenses, and now there is a fairly wide range of pieces of software, either free or commercially available, which allow you to process hemispherical photography to give information like gap fraction, leaf area, and direct and diffuse radiation. These are the sorts of data you want, and you can now do the measurements pretty
rapidly. Although there is a range of assumptions being made here, we generally know what the impacts of those assumptions are on our measurements.

**Measurement: Hemiphotography concept**

- Estimate canopy LAI from gap fraction by classifying hemiphotos

\[
P_0(\theta_v, \varphi_v) = e^{-\lambda_0 G(\theta_v, \varphi_v) \text{LAI} / \cos(\theta_v)}
\]

\[
\text{LAI}_{\text{eff}} = \lambda_0 \text{LAI}_{\text{true}}
\]

Assumes ‘black’ canopy, homogeneous distribution, randomly oriented leaves i.e. no “clumping”

**Fig. 4**

You can use the hemiphotography concept to estimate leaf area from the gap fraction, the probability of seeing the sky from a position. Essentially, that probability is a function of your zenith angle looking upwards, and your azimuth angle looking around you, and an exponential function of the leaf projection (if the leaves are all flat you are less likely to see the sky than if they are all oriented vertically) and the amount of leaf area. So as I say, although there are a bunch of assumptions there, we know a little about those assumptions, and it is a very effective way of characterising the gappiness of the canopy. We can also use multiple measures to give us gap fraction, leaf area, and leaf angle distribution. But we are limited to going and making measurements where we are, out in the field, and where we know what is going on.
I am interested in modelling the light environment so that we can use very detailed models to try and understand the processes and I can say, “What happens if ....?” e.g. “What happens if I take these trees out?” “What happens if I put them very close together?” “What happens if I mix them in terms of species, height and density?” “What happens to the light environment underneath?” I don’t have to go and find an experimental plot where those measurements have been taken, I can do it all in what we call a virtual laboratory. So I am going to talk about one method of doing this, which is called “Monte Carlo Ray Tracing”.

**Monte Carlo Ray Tracing**

**Fig. 5**  
\[ L_{\text{direct}} = \cos(\theta_3) \rho_1^2 \rho_s + \cos(\theta_2) \rho_1 \rho_s \]  
\[ L_{\text{diffuse}} = \rho_1^2 \rho_s^2 \]

“Monte Carlo Ray Tracing” has been around for a while and is used a lot in computer graphics. It is a time-consuming model to run, but very simple, and gives a lot of information. It takes an individual photon and throws it into a scene, a forest if you like, and traces what happens to that photon. The photon bounces around in the scene and then tells the machine where it ends up, does it get absorbed or does it manage to come out of the canopy? It enables us to exploit new measurement methods, making very few assumptions. We don’t have to make assumptions about how the canopy is arranged, for instance we often typically assume that trees are cones on sticks if they are conifers, or spheres on sticks if they are broadleaf, to make life easier for ourselves, but that doesn’t reflect the reality. So, briefly, it is about shining a light into a scene as in the diagram. The purple object is my viewer, and essentially what I do is trace paths through the scene by firing a ray into it. The photon keeps going until it hits something at which point there is a probability that it will be deflected in a certain direction. So lets pick a direction and follow it and see where it gets to, then it might hit something else. I then pick another random direction and repeat, and keep firing photons until I eventually pick up a picture of what is happening. The name Monte Carlo comes from this process of essentially
tossing a coin, gambling. Each time you hit something it is like tossing a coin, you don’t want to sample all directions so you have to pick a small subset in order to build up a picture of what is going on.

The down side of this sort of model is that, although it makes very few assumptions and it is generally easy to come up with a solution, you need information on the canopy structure in the first place. So that is where the complication arises – where do you get this very detailed information? There are quite a few architectural modelling programmes which can be used.

![Scots pine growth using Treegrow model](image)

*Scots pine growth using Treegrow model*  
*Use measured stand info. to build virtual “forests”*

*Fig. 6*  

This is some work we did modelling the light regime in a Scots pine forest in Thetford, Norfolk, which is quite an intensively managed conifer environment. We used a model which was developed for modelling the growth of Scots pine under a range of different conditions, so we were able to model them at different ages, model individual trees and then put them together to create stands of a desired density and age distribution and then look at the light environment in the stand. It requires detailed structure right down to the needle level and we were able to model this forest, with many thousands of trees, down to every individual needle very efficiently. You might wonder what the point is in doing that, but the light regime at the individual shoot level is often what controls the photosynthetic response of the canopy.
Here is a model of a larger managed canopy looking down along the rows of planted stands. You can see the shadowing straight away, and the area where the diffuse factor comes in.

![Scots pine using Treegrow model](image1)

*Fig. 7*  
*Scots pine using Treegrow model*  

Below is a natural birch canopy. We have worked in mountain birch regions in Finland, looking at the light environment and trying to understand the carbon balance; essentially trying to estimate how much biomass there is and understanding how that is going to change with climate change. In the first instance we have to try and estimate the biomass of the standing trees, which is very poorly understood.

![Birch forest based on field measurements in Sweden, Finland & OnyxTREE software](image2)

*Fig. 8*  
*Birch forest based on field measurements in Sweden, Finland & OnyxTREE software*  
*Disney et al. (2009) IEEE TGRSS, 47(10), 3262-3271*
Here is my detailed tree canopy, you can see there are some shrubs in there, and gaps in the soil as well, but once I have got a model like this I can do a whole range of things. I can, for example, put a camera at the bottom of the canopy and say OK how much light is arriving at the bottom of the canopy. The sky is black in this case (just to highlight that), but how much sky can I see, therefore what is the leaf area, therefore what is the mount of branch material and so on, and I can move my camera up through the canopy and look at what the light environment is at all the different levels within the canopy from that point.”

![Fig. 9](image-url) **Fig. 9** Model-simulated hemispherical view looking upwards to the (black) sky from the base of the short-stature birch canopy

Once I have a structural model that I believe represents the canopy reasonably well, I can start doing all sorts of experiments on it. I can take trees out, I can put my camera anywhere in the canopy that I want to and say “What is the amount of direct sunlight, diffuse light from the sky, and canopy-scattered light arriving at this point?”

The image below is an example from inside a very dense Sitka canopy. It is about 9 or 10 years old, so they are quite small trees, but you can see the detail of the individual shoots here. Again you can put the (virtual) camera anywhere in this canopy and simulate the light environment indirectly. The assumption I am making here is that I have some information about the 3D structure and I believe it represents what is going on in that canopy, so that is the big “IF”.

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I can then look at the vertical profile of direct and diffuse radiation, which just falls out of my model because I am modelling all the different levels and tracking where the radiation is going through the canopy and how much of it is attenuated at each interaction. So this is vertical profile through a conifer canopy. The blue and the purple are the direct and the diffuse components of the near infra-red. In vegetation the reflection of the near infra-red is always higher than in the visible red, simply because the plant’s green vegetation absorbs the red whereas it doesn’t absorb the near infra-red. So it is always easier to deal with this signal because it tends to be proportionately much larger. But you can see here that I have a vertical profile down through the canopy and you can also see the difference between the red/near infra-red ratio. A lot of it is being absorbed so there is much less of it left to be reflected.

**Canopy Radiation Distribution**

- Vertical profile of direct, diffuse radiation
- As a function of number of interactions
We can also see, as a function of scattering order (i.e. as a function of the number of interactions that any given photon has had), what happens: how rapidly does the energy decrease with the number of interactions, and the answer is “very quickly”. Most of the energy disappears in the first 2, 3 or 4 interactions. So it is crucial to get those first interactions right if you are trying to understand what is happening to the light. If a photon comes in and is scattered, the fact that it has 100 interactions and then goes off horizontally is not actually very important in terms of photosynthesis.

**Simulate what aircraft/satellite can see**

- Detecting disturbance (management in this case)

![Graph showing NIR Reflectance vs Age (yrs)](image)


This is a simulation of 2 different spacings of a conifer canopy, a very dense area of 2 – 3 metre spacing, and a 8 metre spacing, and shows what aircraft and satellite can see. The dots are the near infrared measurements from the aircraft data, and you can see that there is more and more absorption in the near infra red with age, and then it changes, and what we are seeing is thinning, at the age of about 25 – 30 years. So we are actually detecting disturbance in this case without knowing in advance what was going on.

We can look at other disturbance impacts. The image below is from some work we are doing for an European Space Agency project which is based in South Africa, looking at the impact of burns, and what happens when you have a fire going through a canopy. In these canopies the fire goes through very rapidly, burns all the grass, but leaves the trees and shrubs essentially in tact. We were questioning how that affects the carbon balance and how regeneration occurs. We can model these rather complex environments. The white things here are the large trees and the
dark stuff is the grass cover in the near infra-red, so at the top you have the same scene once you have stripped away all the grass and get left with the little black stubby bits. So again detailed modelling allows us to explore these ‘What if?’ questions. We can also look at the impact of grazing on the patchiness of these things. It turns out to have quite a significant impact because the large animals such as buffalo and elephant follow the same paths over many years and where they trample down the grass it doesn’t get burnt, so they create thin natural firebreaks in these plots which would otherwise burn completely and have an impact on how long it takes to regenerate after fire.

**Disturbance/ management impact: fire**

![Image](image.png)

*Fig. 13*

In the last part of this talk I want to discuss new measurement methods.

My laser pointer is a LIDAR. LIDAR stands for Light Detection And Ranging so it is the optical equivalent of radar. You send out a light signal, bounce it off your target, and measure it coming back. And you measure it as a function of time, the length of time the light beam takes to come back to you tells you how far away the object is, so crudely it is a ranging device. But crucially if you measure the intensity of your signal as it goes out and comes back and chop it up into little sections, it can tell you what is happening to the signal as it is going down through a canopy, for example. So it is quite a powerful measuring tool, and is widely used in forestry applications for measuring tree height. If you send down a signal most of it will bounce off the canopy, but some will reach the ground, and you can separate the bits that come from the top and the bits that come from the bottom and say something about tree height.

However, there are newer instruments which give more accurate height resolution information which are now starting to become routinely used on helicopters and aircraft because they give the vertical distribution of the light profile in the canopy, not just the top and the bottom. They tell you what happens to light attenuation as it goes through the canopy. So again we can simulate what the LIDAR response is here of a single birch tree. To the left, it goes light when the LIDAR signal is hitting
different parts of the tree and then the ground, and on the right is our reflected response as a function of height. So this birch tree is about 5.5 – 6 metres high on flat ground, and this is the red and near infra-red of that tree as a function of this LiDAR signal. So it shows you the profile of light absorption through the canopy as a function of what that tree looks like.

**Lidar signal: single birch tree**

![Image of lidar signal](image)

**Fig. 14**

With this modelling method we can also say what we are seeing: is it leaf, is it branch, what order of branch is it, and so on. So I can separate it into leaf material, woody material, and then to the soil response as well. Not only can I tell what the signal looks like in terms of its vertical profile, I can also tell what material it has bounced back from, which tells me how the canopy is structurally arranged, which of course tells me how it is using the light.

The image below shows what happens if we put a bunch of trees together and look at the canopy. We can see the tops of the tallest trees, then gradually we see shorter trees appearing and little shrubs down at the bottom of the canopy. So we are seeing light attenuating all the way through this footprint. This method allows us to make measurements in areas where we are confounded by the large scale, the remoteness of the location, or the size of the trees. Making measurements of the biomass of trees like this is inherently a difficult thing to do.
Lidar signal: birch canopy

- Simulate what aircraft sees
- Allows far better exploitation of LIDAR measurement

There are new ground-based canopy LIDAR. I can put a LIDAR instrument on the ground and fire it around and I shall get a signal back from the trees that are closest to me, and a weaker response from the ones further away. This has been done a fair bit recently, but with surveying equipment. But surveying lasers are not designed to work in forested environments, they are the wrong wavelength. They also only respond to the first return, so the first time you hit something it accepts that and does not pick up the rest of the signal. But new instruments are being developed.

Echidna is being developed with a CSIRO forestry group in Australia, who have essentially built a laser scanners that scans over the whole hemisphere, which is why it is called Echidna, it is sending out spikes of laser in all directions. It scans over about half an hour or so and is full wave, so you don’t just get the first return, you get a gradation of returns through the canopy. It tells you about the density, it records horizontally, it penetrates out 60 or 80 metres, and it tells you about what is going on above you. So it essentially gives a picture of how light arrives at a point from all directions in that canopy by sending light out and then measuring the return. It is still experimental at the moment.

Below is an Echidna scan of a white fir plantation in Nevada, showing the kind of very detailed information you can get. The bright white tells you that it is closer and denser. We have done similar scans for our birchwoods. This is obviously a modelling study, not a measurement, but it means that you can do the modelling first before you take your $50,000 instrument out there and break it when there are only 2 of them in existence! These kinds of instruments are starting to commercialise quite rapidly because of the information they will give.
To finish then, we want to know what the forest light regime is for a range of different applications, from the point of view of a scientific understanding right through to the management questions, “What happens if I take these out, or grow these here?” The simulation model allows you to do it in a virtual environment where it is cheaper to do because you don’t have to go and carry out replicated experiments, or wait for long periods of time. Yes, there are all sorts of assumptions involved, but you can go out and start to ask these kinds of questions very rapidly. They also help us to exploit new measurement methods, and I think LIDAR is going to be the big advance in understanding light regimes, particularly in forest canopies, over the next 10 year or so. It is already being widely used for tree height, but it can also be used to tell you a lot about canopy structure at the forest scale, particularly from airborne measurements.

There is a new generation of both ground based and air borne sensors in development which are beginning to come on stream and will be more and more operationally useful over the next few years.

Mathias Disney is lecturer in Remote Sensing in the Department of Geography, University College London, and member of the Environmental Monitoring and Modelling Group, and the Geographical Information Science and Remote Sensing Network. “I am interested in the interactions of radiation (predominantly at optical wavelengths) with the land surface. In particular I am interested in how radiation interacts with vegetation, how we can model and understand this interaction and how we can exploit it to quantify and understand the terrestrial biosphere. Much of my research effort has been directed at new ways of exploiting observations of the land surface to estimate biophysical parameters related to vegetation type, amount and dynamics. One of the key ways in which I do this is by developing highly detailed models of tree and plant canopies in order to simulate the radiation regime with as few assumptions as possible, and then compare simulations with both observations, and simpler models.”