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# Satellite-driven modelling of Net Primary Productivity (NPP): Theoretical analysis

Ana Prieto-Blanco [a,b,*], Peter R.J. North [a,b], Michael J. Barnsley [a,b,1], Nigel Fox [b]

[a] NERC CLASSIC, University of Wales, Swansea, UK
[b] Department of Geography, University of Wales, Swansea, UK
[c] National Physical Laboratory, Teddington, Middlesex, UK

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ABSTRACT

Ecological models are central to understanding the global hydrological and carbon cycles, and need data from Earth Observation to function effectively at regional to global scales. Here, we develop and apply an end-to-end analysis that relates the requirements of ecological models to the capabilities of satellite-sensors, starting with radiometric noise at the instrument, which collects the information, running through to the error on the estimated NPP output from the ecological model. In the process, the input requirements of current ecological models are reviewed. Our aim is to establish a better informed framework for the design and development of future satellite-sensor missions, which meet the needs of ecological modellers. Three mathematical models (PROSPECT, FLIGHT and 6S) are coupled and inverted using a technique based on LUT. The LUT are used to estimate biophysical variables of vegetation canopies from remotely-sensed data observed at the TOA in a number of viewing directions and in several wavebands within the visible and near-infrared spectrum. The five variables considered here are LAI, leaf chlorophyll content ($C_{ab}$), fAPAR, cover fraction and AOT. Different sensor configurations are investigated, in terms of directional and spectral sampling. The retrieval uncertainty is linked with the instrument radiometric accuracy by analysing the impact of different levels of radiometric noise. The parameters retrieved via the inversion are used to drive two LSP models, namely Biome-BGC and JULES. The effects of different sensor configurations and levels of radiometric noise on the NPP estimated are analysed. The system is used to evaluate the sensor characteristics best suited to drive models of boreal forest productivity. The results show that multiangular information improves dramatically the accuracy with which forest canopy properties are estimated. Due to problems of equifinality, the results show a persistence of error even in the presence of zero noise from the sensor, although decreasing the level of radiometric noise from 0.02 to 0.001 reduces error in the estimated NPP by 10% to 25%.

## 1. Introduction

Diagnosis and prediction of climatic, environmental and ecological changes in the Earth system is an enormously challenging task (IPCC, 2001, 2007). Better understanding of the processes involved, including those relating to Earth's radiation budget, atmospheric aerosol transport, vegetation and climate interactions, and carbon cycle, is required to address issues ranging from climatic change to environmental degradation. Ecological studies have traditionally focused on in situ observations of specific species at individual sites. These observations must be applied across a range of scales to address the needs of regional and global studies and to provide the broader insight needed of the entire Earth system. Ecological and climatic models allow us to extrapolate the physical processes, such as photosynthesis, respiration and evapotranspiration, which are measured at the leaf and canopy scale, to larger regions and longer temporal scales. Models are, therefore, a fundamental tool and their requirements an important input to the design of future satellite-sensor missions.

### 1.1. Requirements for biophysical parameters

Land-surface process (LSP) models describe the physiological and biophysical processes of soil and vegetation, including ecosystem Net Primary Productivity (NPP). Models of this type have assumed greater importance in recent years, and are now commonly incorporated to global climate models (Cox et al., 1999; Cramer et al., 2001). Land-surface process (LSP) models are also analysed in their own right to understand better the global carbon cycle (Kimball et al., 1997a,b; Potter et al., 2003). LSP models require information on a number of land-surface properties (e.g., land cover, leaf area index (LAI), roughness length and albedo), which are used to characterize the state of the land-surface and atmosphere system, in addition to meteorological data (e.g., daily values of maximum and minimum air temperature, total solar radiation, mean humidity and total precipitation). Satellite remote sensing can provide some of these inputs, and reference values to check the model outputs, at the required temporal and spatial scales (Chen et al., 2003; Lambin & Linderman 2006; Turner et al., 2006).

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[*] Corresponding author. Department of Geography, University of Wales, Swansea, UK. *E-mail address:* prieto@geog.ucl.ac.uk (A. Prieto-Blanco).

[1] Deceased.

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**Table 1**
Requirements for land-surface modelling

| | Source | Spatial resolution | Temporal resolution | Accuracy |
|---|---|---|---|---|
| Aerosol — total column | GCOS,GTOS | 1 km, 5 km | 24 h | – |
| | WMO | 50 km, 100 km | 0.25 h, 1 h | 10%, 10% |
| | IGBP | | 7 d | 10% |
| Albedo | Sellers et al. (1995) | 250 km | 30 d, 1 d, diurnal cycle | ±0.02 |
| Cloud imagery | GCOS, GTOS | 1 km | 3 h | – |
| Downwelling long-wave radiation at the Earth surface | GCOS, GTOS | 25 km | 3 h | ±5 W/m$^2$ |
| Downwelling short-wave radiation at the Earth surface | GCOS, GTOS | 25 km | 24 h | ±5 W/m$^2$ |
| Downwelling solar radiation at TOA | GCOS | – | 3 h | ±1 W/m$^2$ |
| Fire area/temperature | GCOS,GTOS | 0.1 km | 10 d | 5%/50 K |
| | IGBP | 3 km | 10 d | 5%/200 K |
| | UNEP | 0.5 km | 1 d | 5%/50 K |
| fAPAR | GCOS | 0.1 km | 10 d | 5% |
| | IGBP | 0.03 km, 50 km | 10 d | 5% |
| Land cover | WMO | 10 m, 100 m | 0.02 y, 1 y | 50 classes, 10 classes |
| | GCOS, GTOS | 100 m | 1 y | 50 classes |
| | IGBP | 30 m, 100 m, 1 km | 1 y | 22, 22, 2 classes |
| | UNEP | 1 m | 1 y | 20 classes |
| Land-surface imagery | GCOS, GTOS | 1 m | 4 y | – |
| | WMO | 10 m | 1 d | – |
| Land-surface topography | GCOS, GTOS | 10 m | 10 y | 30 (vert) |
| | WMO | 100 m | 10 y | 1 m (vert) |
| | IGBP | 10 m, 1 km | 100 y | 0.3 m, 1 m (vert) |
| LAI | GCOS, GTOS | 0.1 km | 10 d | 20% |
| | WMO | 0.01 km, 10 km, 50 km | 5 d, 7 d, 7 d | 5% |
| Land cover | GCOS | 0.1 km | 1 y | 50 classes |
| | WMO | 0.01 km, 0.1 km | 0.02 y, 1 y | 50, 10 classes |
| | IGBP | 0.03 km, 0.1 km, 1 km | 1 y | 22, 22 and 2 classes |
| | UNEP | 1 m | 1 y | 20 classes |
| Outgoing long-wave Earth surface | GCOS, GTOS | 25 km | 3 h | ±5 W/m$^2$ |
| Outgoing long-wave radiation at TOA | GCOS, GTOS | 50 km, 200 km | 20 d, 3 h | ±5 W/m$^2$ |
| | WMO | 0.1 km, 10 km, 50 km | 1 h, 0.5 h, 1 h | ±5 W/m$^2$ |
| | IGBP | 200 km | 6 h | ±10 W/m$^2$ |
| Ozone profile — total column | GCOS, GTOS | 1 km | 24 h | – |
| | WMOS | 10 km, 20 km, 25 km, 50 km | 0.5 h, 0.25 h, 6 h, 1 h | 5 DU (Dobson units) |
| PAR | Sellers et al. (1995) | 250 km | 30 d, 1 d, diurnal | ±10 W/m$^2$ |
| | WMO | 5 km | 1 h | 5% |
| Snow cover | GCOS, GTOS | 1 km, 100 km | 24 h | 5%, 10% |
| | WMO | 0.1 km, 1 km, 5 km, 15 km | 24 h, 120 h, 1 h 12 h | 5%, 2%, 10%, 10% |
| | WCRP | 1 km, 15 km | 24 h | 10% |
| Short-wave Earth surface bidirectional reflectance | Sellers et al. (1995) | 250 km | 30 d | ±10 W/m$^2$ |
| | WMO | 25 km | 24 h | ±5 W/m$^2$ |
| | IGBP | 100 km | 7 d | 1% |
| Vegetation type | WMO | 10 m, 50 m, 50 km | 7 d, 30 d, 7 d | 50, 30, 18 classes |
| | IGBP | 10 m, 100 m, 1 km | 10 d, 1 y, 90 d | 2, 18, 18 classes |
| | UNEP | 1 m | 1 y | 18 classes |

Only optimum values are shown.
Sources: ISLSCP Workshop (Sellers et al., 1995); Global Climate Observing System (GCOS); World Meteorological Organization (WMO); Global Terrestrial Observing System (GTOS); International Geosphere–Biosphere Programme (IGBP); World Climate Research Programme (WCRP); United Nations Environmental Program (UNEP). CEOS/WMO database, Observational requirements (WMO, WCRP, GCOS, GOOS, GTOS, IGBP, ICSU, UNEP).

Increasing availability of remotely-sensed data (Diner et al., 2005; Friedl et al., 2002) and growing interest in quantifying the terrestrial carbon flux (Canadell et al., 2003; IPCC, 2001) have driven forward research on the integration of LSP models and satellite remote sensing (Kimball et al., 1997a; Plummer 2000; Sellers et al., 1997a; Turner et al., 2004). The present tendency is toward "model–data synthesis" (Raupach et al., 2005), a combination of models and observations, which involves both parameter estimation and data assimilation techniques. In this approach, the uncertainties involved are as important as the parameter values. It is critical to define the requirements of LSP models from satellite remote sensing with a view to defining the characteristics of future satellite-sensor missions. Uncertainties associated with the parameters retrieved by remote sensing are hard to quantify as the ground truth measurements, where available, must be scaled up to larger areas to be compared with the satellite-sensor data (Heinsch et al., 2006; Morisette et al., 2002). Future satellite missions are now being designed taking into account the requirements of the users, often expressed as end-product specifications (Townshend and Justice 2002). These requirements are slowly being refined with input from the broad science community (Sellers et al., 1995, Townshend and Justice 2002, Table 1).

### 1.2. Retrieval of biophysical parameters from satellite observations

Many biophysical data sets, notably those derived from long-term NOAA/AVHRR observations, are derived empirically from spectral reflectance measurements, using so-called vegetation indices such as the normalized difference vegetation index (NDVI), which employs information from the visible and near-infrared spectral regions (Los et al., 2005). Ideally, however, the physics underpinning the relationships between various environmental properties and satellite-sensor measurements of spectral reflectance should be represented explicitly, expressed analytically in mathematical terms (Verstraete et al., 1996). The resulting "physically-based" models can then be inverted against multispectral and multiangular measurements of surface reflectance to retrieve estimates of the models' driving parameters (i.e., the biophysical properties of the reflecting surface).