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# Refining light-use efficiency calculations for a deciduous forest canopy using simultaneous tower-based carbon flux and radiometric measurements

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**Abstract**

The concept of light-use efficiency (LUE) is the underlying basis for estimating carbon exchange in many ecosystem models, especially those models that utilize remote sensing to constrain estimates of canopy photosynthesis. An understanding of the factors that control the efficiency with which forest canopies harvest available light to fix carbon via photosynthesis is therefore necessary for the development of useful production efficiency models. We present an analysis of observations of daily LUE for 2004 in a northern hardwood stand at the Bartlett Experimental Forest $CO_2$ flux tower, White Mountains, New Hampshire (USA). We used eddy covariance measurements to estimate gross carbon exchange (GCE), and radiometric instruments mounted above and below the canopy to estimate the fraction of incident photosynthetically active radiation absorbed by the canopy ($f$APAR). Both GCE and $f$APAR show strong seasonal and day-to-day variability that contribute to temporal variation in LUE. During the middle of the growing season, when $f$APAR is relatively constant, day-to-day variation in LUE is largely explained ($r^2 = 0.85$) by changes in the ratio of diffuse to total downwelling radiation, but is not strongly correlated with any other measured meteorological variable.

We also calculated top-of-canopy NDVI based on measurements of reflected radiation at 400–700 and 305–2800 nm. Seasonal variation in this broadband NDVI paralleled that of the 500 m MODIS pixel containing the flux tower. The relationship between broadband NDVI and $f$APAR is approximately linear during green-up, but non-linear during autumn senescence. This seasonal hysteresis has implications for the use of remote sensing indices (such as NDVI or EVI) in satellite estimation of $f$APAR for production efficiency modeling.


*Keywords:* AmeriFlux; Bartlett Experimental Forest; Canopy optics; Eddy covariance; $f$APAR; LAI; Light-use efficiency; MODIS; NDVI; Phenology; Reflectance; Remote sensing

## 1. Introduction

One of the greatest sources of uncertainty in predictions of future climate scenarios can be attributed to a lack of knowledge about the terrestrial carbon cycle, particularly as related to the future levels of atmospheric $CO_2$ (IPCC Third Assessment; Houghton

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et al., 2001; Schimel et al., 2004). Our current knowledge of how $CO_2$ sources and sinks are distributed among and between the major landmasses in the northern hemisphere is relatively poor (Running et al., 1999). Understanding the controls on spatial and temporal patterns of surface–atmosphere $CO_2$ exchange is therefore needed so that improved predictions of future levels of atmospheric $CO_2$ can be made.

Many existing broad-scale models of ecosystem carbon exchange (e.g., MODIS GPP: Turner et al., 2003a; Zhao et al., 2005; CASA: Potter et al., 1993; GLO-PEM: Prince and Goward, 1995; VPM: Xiao et al., 2004) rely on estimates of photosynthetic light-use efficiency (LUE), that is, the amount of carbon fixed per unit of absorbed solar radiation:

$$P = \varepsilon \times f\text{APAR} \times \text{PAR} = \varepsilon \times \text{APAR} \quad (1)$$

where $P$ is carbon fixed through photosynthesis, $\varepsilon$ the light-use efficiency and APAR is the absorbed photosynthetically active radiation (PAR).

These estimates are often derived from physiological models or vegetation-specific look-up tables. In a production efficiency modeling (PEM) framework (Ollinger et al., in press), the LUE concept is combined with remote sensing estimates of leaf area index (LAI) and/or the fraction of absorbed photosynthetic radiation ($f$APAR) to predict primary productivity as a function of integrated daily or monthly downwelling solar radiation. Relationships used in these models are derived from Monteith's (1972) finding that productivity is a linear function of PAR intercepted by the canopy.

While remote sensing is the principal tool used to develop spatially extensive estimates of gross primary productivity (Running et al., 2004), detailed analyses of the performance of remote sensing based PEM algorithms are still needed (Turner et al., 2003b). For example, a persistent challenge for PEM algorithms in general has been the lack of understanding concerning factors controlling variation in LUE both within and among vegetation types; individual studies have suggested that LUE varies with factors such as stand age, species composition, soil fertility and foliar nutrients (Gower et al., 1999). Additionally, the relationship between the optical remote sensing based normalized difference vegetation index (NDVI) and $f$APAR is generally considered to be near-linear (Sellers, 1985; Ruimy et al., 1994; Paruelo et al., 1997; Los et al., 2000) and consequently NDVI is frequently used with an estimate of maximum LUE in PEM models to calculate productivity (Ruimy et al., 1999).

For a specific ecosystem, the light-use efficiency could be calculated by making observations of two key variables from Eq. (1): (1) rates of gross photosynthetic uptake ($P_{gross}$) by the system, and (2) the amount of incident PAR that is absorbed by the canopy (APAR; or, when expressed as a fraction of downwelling radiation, $f$APAR). Networks of carbon flux towers (such as AmeriFlux and FLUXNET), where the surface–atmosphere exchange of $CO_2$ is being measured continuously in a wide range of ecosystems (Baldocchi et al., 2001), provide net ecosystem exchange, which can be used to estimate gross carbon exchange (GCE), a measure of $P$. Existing tower infrastructures also make it possible to conduct the necessary partitioning of the canopy radiation budget so that APAR can be determined. With these data, LUE, which has units of mol C per mol photon, could then be calculated as GCE/APAR.

In this paper, we present a comprehensive analysis of the factors affecting LUE in a northern hardwood forest in north-central New Hampshire, USA. We explore both annual and daily timescales as even PEMs which operate at this time step (Lagergren et al., 2005) generally assume constant annual LUEs. In addition, we investigate seasonal changes (i.e., phenology) in the optical properties of the canopy, as indicated by the temporal patterns of transmittance and reflectance. We use broadband radiation sensors to separately quantify changes in the reflectance of visible (VIS) and near-infrared (NIR) radiation.

## 2. Data and methods

### 2.1. Study site

The Bartlett Experimental Forest (44°17′ N, 71°3′ W) is located within the White Mountains National Forest in north-central New Hampshire, USA. The 1050 ha forest extends across an elevational range from 200 to 900 m a.s.l. It was established in 1931 and is managed by the USDA Forest Service Northeastern Research Station in Durham, NH. The climate is humid continental with short, cool summers (mean July temperature, 19 °C) and long, cold winters (mean January temperature, −9 °C). Annual precipitation averages 130 cm and is distributed evenly throughout the year. Soils are developed from glacial till and are predominantly shallow, well-drained spodosols. At low- to mid-elevation, vegetation is dominated by northern hardwoods (American beech, *Fagus grandifolia*; sugar maple, *Acer saccharum*; yellow birch, *Betula alleghaniensis*; with some red maple, *Acer rubrum* and paper birch, *Betula papyrifera*). Conifers (eastern hemlock,