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Evaluation of optical remote sensing to estimate actual evapotranspiration and canopy conductance

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ABSTRACT

We compared estimates of actual evapotranspiration (ET) produced with six different vegetation measures derived from the MODerate resolution Imaging Spectroradiometer (MODIS) and three contrasting estimation approaches using measurements from eddy covariance flux towers at 16 FLUXNET sites located over six different land cover types. The aim was to assess optimal approaches in using optical remote sensing to estimate ET. The first two approaches directly regressed various MODIS vegetation indices (VIs) and products such as leaf area index (LAI) and fraction of photosynthetically active radiation (fPAR) with ET and evaporative fraction (EF). In the third approach, the Penman–Monteith (PM) equation was inverted to obtain surface conductance (G_s), for dry plant canopies. The G_s values were then regressed against the MODIS data products and used to parameterize the PM equation for retrievals of ET. Jack-Knife cross-validation was used to evaluate the various regression models against observed ET. The PM-G_s approach provided the lowest root mean square error (RMSE), and highest determination coefficients (R^2) across all sites, with an average RMSE = 38 W m^{-2} and $R^2=0.72$. Direct regressions of observed ET against the VIs resulted in an average RMSE = 60 W m^{-2} and $R^2=0.22$, while the EF regressions an average RMSE = 42 W m^{-2} and $R^2=0.64$. The MODIS LAI and fPAR product produced the poorest estimates of ET (RMSE > 44 W m^{-2} and $R^2<0.6$); while the VIs each performed best for some of the land cover types. The enhanced vegetation index (EVI) produced the best ET estimates for evergreen needleleaf forest (RMSE = 28.4 W m^{-2}, $R^2=0.66$). The normalized difference vegetation index (NDVI) best estimated ET in grassland (RMSE = 23.8 W m^{-2} and $R^2=0.68$), cropland (RMSE = 29.2 W m^{-2} and $R^2=0.86$) and woody savannas (RMSE = 25.4 W m^{-2} and $R^2=0.82$), while the VI-based crop coefficient (K_c) yielded the best estimates for evergreen and deciduous broadleaf forests (RMSE = 27 W m^{-2} and $R^2=0.7$ in both cases). Using the ensemble-average of ET as estimated using NDVI, EVI and K_c we computed global grids of dry canopy conductance (G_c) from which annual statistics were extracted to characterise different functional types. The resulting G_c values can be used to parameterize land surface models.

1. Introduction

Remote sensing is the only feasible means of spatially estimating actual evapotranspiration (ET) over large regions or continents. Various approaches developed to derive ET from remote sensing data can be broadly grouped into: (i) those incorporating satellite land surface temperature into a surface energy balance (SEB) model (Kalma et al., 2008), (ii) those using vegetation indices (VIs) (Glenn et al., 2010, 2011b) and (iii) hybrid methods that combine the surface temperature and vegetation index data (Carlson, 2007; Tang et al., 2010).

VI based approaches are increasingly being explored, partly because SEB methods have been difficult to implement over large areas and because the number of satellite sensors that have thermal infrared bands is still limited (Glenn et al., 2010). Moreover the surface and near surface meteorological variables at the specific time that remotely sensed data is acquired required to solve a SEB model (e.g. air temperature, relative humidity and solar radiation) are difficult to obtain from daily meteorological data which highly complicates data processing (McVicar & Jupp, 1999).

VI methods depend on an estimate of the density of green vegetation over the landscape (Glenn et al., 2010). Although VIs cannot detect soil evaporation nor vegetation stress except on a long time basis (Kalma et al., 2008) several studies have found that they provide better estimations of ET than thermal bands. For example, Cleugh et al. (2007) compared MODerate resolution Imaging Spectroradiometer

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(MODIS)-based SEB and VI methods against ground measurements of ET in Australia. The SEB methods failed because small errors in land surface temperatures translated into large errors in estimates of sensible heat in the SEB equation, and hence in ET. By contrast, the VI model adequately estimated ET. Similarly, a recent study by King et al. (2011) and summarized by Glenn et al. (2011a) compared different remote sensing-based ET methods, including those based on thermal imagery (McVicar & Jupp, 1999), VIs (Guerschman et al., 2009), MODIS derived LAI (Zhang et al., 2010) and multiple remote sensing data sources (Mu et al., 2007) and concluded that the best performing method was that one based on VIs (RMSE of 0.65 against 0.87 mm $d^{-1}$for the thermal method).

Commonly used VIs include the normalized difference vegetation index (NDVI) (Fisher et al., 2008; Zhang et al., 2009), the enhanced vegetation index (EVI) (Leuning et al., 2005; Mu et al., 2007; Yuan et al., 2010), the normalized difference water index (NDWI) (Lu & Zhuang, 2010) and modelled satellite products such as leaf area index (LAI) (Cleugh et al., 2007; Leuning et al., 2008; Mu et al., 2007) and the fraction absorbed photosynthetically active radiation (fPAR) (Van Dijk, 2010).

The VIs are typically used in one of two ways: (i) directly, to retrieve ET through an empirical relationship between ground measurements of ET (typically from flux towers) or evaporative fraction (EF) (Nishida et al., 2003), or (ii) to parameterize the conductance term of the Penman Monteith (PM) equation (Leuning et al., 2008) (see (Glenn et al., 2010; Glenn et al., 2011a) for a comprehensive review of approaches).

Despite the success of various VI-based techniques, there is no consensus on the most appropriate way to use optical remote sensing to estimate ET. The main objective of this study was to compare and evaluate the performance of three contrasting approaches and six different MODIS-derived vegetation measures to retrieve ET and thus determine the best use of optical remote sensing to estimate ET across and within land cover types.

2. Methods and data sources

The general scheme of the method developed in this paper is presented in Fig. 1. Meteorological and flux data derived from eddy covariance flux towers as well as reflectances derived from MODIS were used to test three contrasting approaches to estimate ET; (i) direct regression, (ii) potential evapotranspiration (PET) scaling and (iii) PM conductance approach (PM-G_s). Each approach was tested using six different MODIS-derived vegetation measures. The estimates

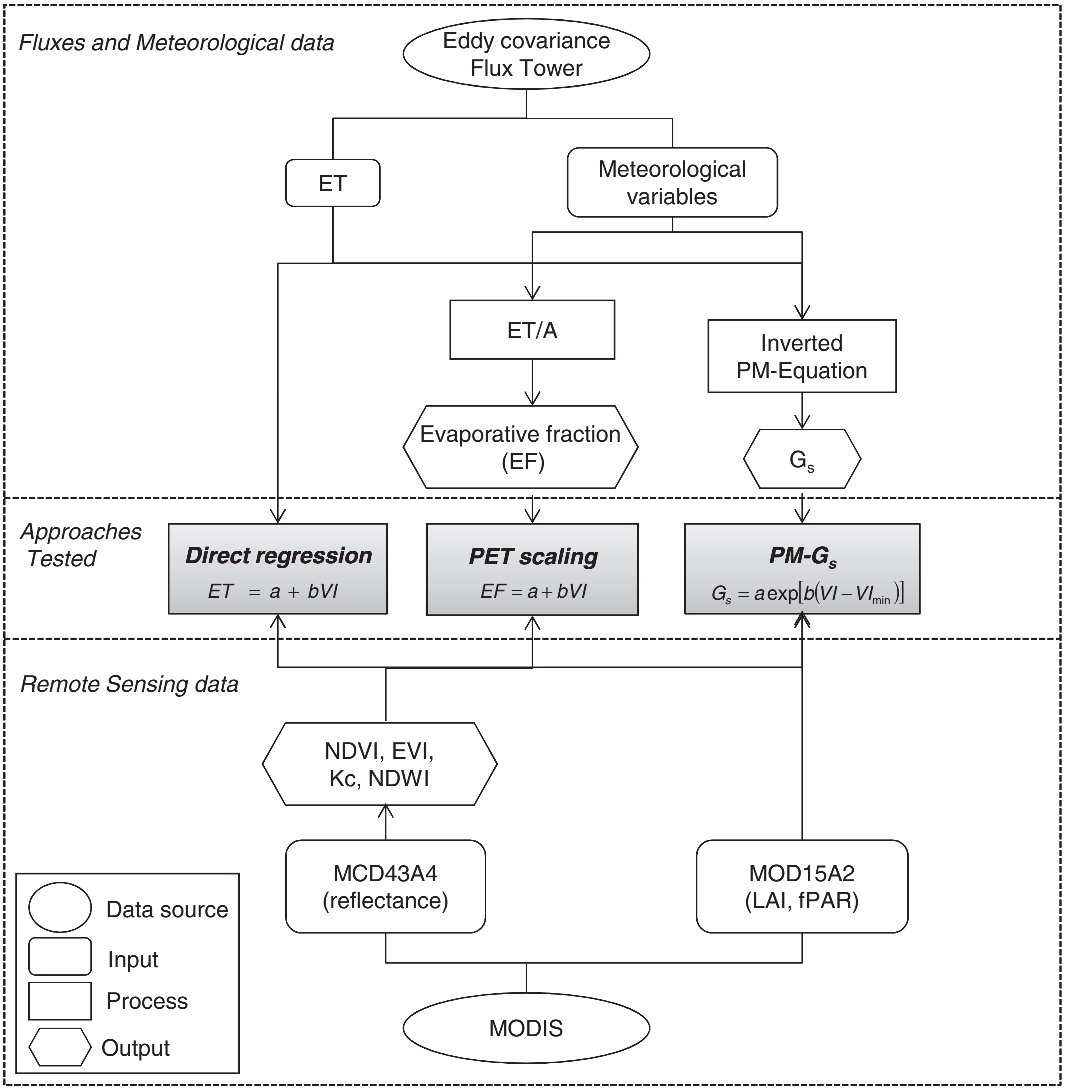

Fig. 1. Methodological flowchart. MODIS Nadir BRDF-adjusted reflectance (MCD43A4) and LAI/fPAR products (MOD15A2) were combined with flux and meteorological data average over 16-days to derive ET (direct regression), EF (PET scaling) and surface conductance (PM-G_s).