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Monitoring and forecasting ecosystem dynamics using the Terrestrial Observation and Prediction System (TOPS)

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ABSTRACT

We present an approach for monitoring and forecasting landscape level indicators of the condition of protected area (PA) ecosystems including changes in snowcover, vegetation phenology and productivity using the Terrestrial Observation and Prediction System (TOPS). TOPS is a modeling framework that integrates operational satellite data, microclimate mapping, and ecosystem simulation models to characterize ecosystem status and trends. We have applied TOPS to investigate trends and patterns in landscape indicators using test cases at both national and park-level scales to demonstrate the potential utility of TOPS for supporting efforts by the National Park Service to develop standardized indicators for protected area monitoring. Our analysis of coarse resolution satellite-derived normalized difference vegetation index (NDVI) measurements for North America from 1982–2006 indicates that all but a few PAs are located in areas that exhibited a sustained decline in vegetation condition. We used Yosemite National Park as our park-level test case, and while no significant trends in NDVI were detected during the same period, evidence of drought-induced vegetation mortality and recovery patterns dominated the 25-year record. In our Yosemite analysis, we show that analyzing MODIS (Moderate Resolution Imaging Spectroradiometer) products (vegetation indices, absorbed radiation, land surface temperature and gross primary production) in conjunction with ground-based measurements, such as runoff, lends additional utility to satellite-based monitoring of ecosystems indicators, as together they provide a comprehensive view of ecosystem condition. Analyses of MODIS products from 2001–2006 show that year-to-year changes in the onset of spring at Yosemite were as large as 45 days, and this signal in the satellite data record is corroborated by observed changes in spring runoff patterns. Finally, we applied TOPS to assess long-term climate impacts on ecosystem condition at the scale of an individual park. When driven by projected climatic changes at Yosemite of 4–6 °C warming by 2100 with no changes in precipitation patterns, TOPS predicts significantly reduced winter snowpack and an earlier onset of the growing season, resulting in prolonged summer drought and reduced vegetation productivity.

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1. Introduction

Human transformation of the Earth has been so pervasive that only protected areas (PAs), such as national parks and reserves, retain a semblance of nature. The World Conservation Union estimates that global conservation efforts over the past three decades resulted in a phenomenal expansion of PAs, such that they now cover nearly 12.4% of Earth's land surface (Chape et al., 2003). In spite of these conservation efforts, studies have shown that the global distribution of PAs may not be optimum for conserving biodiversity (Rodrigues et al., 2004). Current conservation plans assume that the geographic distribution of species changes slowly, unless they are directly impacted by human activities. Recent studies, however, show that projected changes in climate could significantly alter such plans, requiring the establishment of new PAs or the expansion of existing PAs as the ability of current PAs to protect species diversity diminishes in the future (Hannah et al., 2007). Climate change is an important issue for many PAs in the US, particularly those in the western U.S., where significant climate impacts are already being felt (Fagre et al., 1997). Since the 1950s, remarkable changes have been reported in landscape dynamics, including shifts in the onset of spring, the timing and magnitude of surface runoff, and changes in fire regimes. Many of these recent changes are largely attributed to widespread warming

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(Hayhoe et al., 2004; Cayan et al., 2001; Dettinger et al., 2004; Westerling et al., 2006). If the current trajectory continues, climate change is likely to bring unprecedented changes to PA ecosystems and simply setting aside land may no longer be sufficient to conserve biodiversity. To assess the condition of existing protected areas we need to continuously inventory, monitor and predict both ongoing and potential changes in ecosystem conditions. Furthermore, monitoring efforts must be conducted using well documented and repeatable methods that provide consistent and comparable assessments.

Monitoring of pedological, biological, and climatological resources is expensive and time consuming, and is often difficult to accomplish within limited budgets (Herrick 2000; Palmer et al., 2002; Schreuder & Czaplewski, 1993). Fancy et al. (2009) describe a comprehensive inventory and monitoring (I&M) program for the National Park Service (NPS) that includes indicators such as changes and variability in climate, exotic plant species occurrence, vegetation cover and type, changes in snowcover, water quality and quantity, vegetation productivity and phenology. Indicators are designed to track changes in park "vital signs", which are selected by parks to "represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values" (Fancy et al., 2009). Satellite data could be a key component of executing such a monitoring program. Remotely sensed data, desired in PA assessment because of the low data collection footprint, have been used to map features such as burned areas, burn severity, land cover type, and invasive species extent (Gross et al., 2006; Cohen & Goward 2004). One benefit of remote sensing for PA monitoring is that it provides complete spatial coverage, versus point or plot samples from which it may be difficult to provide an overall assessment for the entire PA. Historically, however, remote sensing studies over PAs have been largely limited to the use of very high spatial resolution (but low temporal resolution) satellite or airborne data. These studies, though providing the best inventory of PA resources, tend to be expensive, complex, and difficult to repeat.

Recent advances in moderate resolution remote sensing data offer a strategic complement to high spatial resolution inventories. Satellite-based data from sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) offer daily/weekly data at a resolution of 250–1000 m (Justice et al., 1998). Data from MODIS provide a capability for regular ecosystem monitoring for PA vital sign indicators such as phenology, snow cover, surface temperature, and vegetation productivity. State-of-the art processing algorithms facilitate accurate geometric, radiometric and atmospheric corrections leading to robust estimates of land surface properties that can be directly used in monitoring systems. These newly available operational products, when integrated into the I&M program or other PA monitoring systems, have immense and yet to be realized potential for PA management. Lack of remote sensing expertise and the need for large computational resources, beyond the scope of many PA stewardship organizations, are often cited as key issues for their limited use to date.

While satellite or ground-based data can provide information about trends and variability in key ecosystem properties, understanding the mechanisms behind them involves careful analysis of additional data, such as climate records and estimates from simulation models. Models are particularly important for predicting the future states of ecosystems that may result from various forcings, such as climate change and land use changes, as analysis of these forcings requires the use of simulation models (Running et al., 1989; Nemani et al., 2003a). Such models, when properly calibrated and tested, are valuable tools for asking "what if" questions that allow PA managers to assess the impacts of external forcings and various management options. For example, models such as the Regional Hydro-Ecological Simulation System (RHESSys) have been used to predict changes in ecosystem properties in response to climate change over national parks (Baron et al., 2000). While valuable, the scientists conducting these modeling analyses rarely have sufficient resources to adapt the models for use in an operational setting.

All the key components of a system that could accomplish monitoring, modeling, and forecasting of PA ecosystems exist at various levels of sophistication. What is needed is to integrate these components into a robust system that PA personnel, who often lack the experience in various components, can use operationally. Here we describe our efforts at building such an integrated system. Funded by the National Aeronautics and Space Administration (NASA), the Terrestrial Observation and Prediction System (TOPS) is a data and modeling software system designed to seamlessly integrate data from satellite, aircraft, and ground sensors with weather, climate, and application models to expeditiously produce operational nowcasts and forecasts of ecological conditions (Fig. 1, Nemani et al., 2003a, 2007; White & Nemani 2004; Ichii et al., 2008). TOPS provides reliable data on current and forecasted ecosystem conditions through automation of the data retrieval, preprocessing, integration, and modeling steps, allowing TOPS data products to be used in an operational setting for a range of applications. TOPS is designed and implemented following the principles laid out in the Global Earth Observing System of Systems implementation plan (GEOSS, 2005).

Though TOPS has already been used in the development of a variety of applications, from simulating irrigation requirements of vineyards to monitoring global net primary production (Nemani et al., 2003b; Nemani et al., 2007), its application for PA management leverages all of its key components: monitoring, modeling and forecasting, as well as a sophisticated data gateway that will allow access to organized and highly customized information.

This paper is organized as follows: first, we describe TOPS and its components; second, we provide a continental analysis of PA ecosystems over the past 25 years (1982–2006) using coarse resolution satellite data; third, using Yosemite National Park (hereafter referred to as Yosemite) as a demonstration of TOPS regional analysis capabilities, we evaluate the application of moderate resolution satellite data for monitoring park vital signs, understanding ecosystem controls of interannual variability using simulation models, and forecasting the impact of potential climatic changes on Yosemite ecosystems; and fourth, we describe a data gateway for accessing TOPS data and information.

2. Terrestrial Observation and Prediction System

2.1. TOPS overview

The concept behind TOPS originated with earlier work on the integration of satellite data with ecosystem models (Running et al., 1989; Nemani et al., 1993). This effort required careful adaptation of one-dimensional simulation models to a two-dimensional land surface, which required spatially continuous, gridded data on soils, vegetation and climate (Running et al., 1989). Satellite data provided the necessary data inputs for much of the required information on land use/land cover, and for estimates of biophysical properties such as vegetation leaf area index (LAI) (Nemani et al., 1993). Spatial aggregation of landscapes into functionally similar units and routing of water between and among these units for simulating streamflows came next (Band et al., 1993; Tague & Band, 2004). Sophisticated gridding routines helped in the creation of spatially continuous climate fields using a limited number of climate observations (Thornton et al., 1997; Jolly et al., 2005). TOPS leverages this historical work, focused primarily on retrospective analysis of ecosystems, and includes additional functionality that enables simulation models to be run in near real-time, which provides a new capability for operational nowcasts and forecasts. During the past two decades, advances in information technology including the rapid expansion of the world wide web, exponential increases computing power and storage, and