Satellite-derived Vegetation Dynamics Applied to Post-fire Vulnerability Assessment in Eastern Spain [1]

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Abstract

Wildland fire and subsequent weather/climate events can have a devastating impact on the sustainable use of dryland resources, leaving physical and human landscapes vulnerable to secondary effects of land degradation and potentially undesirable changes in vegetation dynamics and fire regime. This is particularly the case in the semi-arid Mediterranean region where a long, dry, fire-prone season is followed by a period of potentially intensive rainfall on generally steep slopes, lithographically fragile soils and a topography that is complex due to traditional land management. Strategic planning involves the use of decision frameworks, which in practice tend to be based on the converging lines of evidence (i.e., cartographic erosion risk models, synoptic data for landscape assessment, ground measurements and observations, expert knowledge) to identify areas where erosion risk is high and vegetation regeneration may be difficult following wildland fire. While cartographic models provide managers some insight into those locations most vulnerable to landscape degradation, the seasonality of rainfall and vegetative cover are generally not taken into account. Moreover, base maps derived from fine resolution imagery become obsolete over time as fires occur and recovery proceeds at rates which vary relative to burn severity and other factors which influence vegetation composition and phenology. This study addressed temporal biophysical dynamics of post-wildfire landscape vulnerability in eastern Spain through the derivation of the RUSLE C-factor from multi-temporal MODIS NDVI data. The effectiveness of this approach was assessed with ground measurements (multi-temporal sediment data and periodic vegetation assessments from study sites in Alicante and Valencia). MODIS-derived C-Factor dynamics were related to post-fire bare-soil cover dynamics in a small watershed in Guadalest site (Alicante), and helped explain post-fire sedimentation dynamics in Calderona site (Valencia). Recovery dynamics of post-fire vegetation in eight burned watersheds in Millares site (Valencia), measured as satellite-derived RUSLE C-factor, were significantly related to the cumulated sediment yield produced in the watersheds along a 10-year period after the wildfire. These results point to the potential of the this approach as a tool for rapid and cost-effective assessments of post-fire ecosystem recovery, which ultimately could be applied to large areas and used to analyze vulnerability factors at the regional scale.

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Introduction

Large areas of global drylands are facing the risk of desertification and catastrophic wildland fire. This risk is projected to increase under many climate scenarios (Easterling 2000), leading to more frequent and intense droughts and more extreme rainfall events. In the Mediterranean, climate warming and associated droughts (Sanchez and others 2004) will result in an increased probability of wildland fire (Piñol and others 1998, Moriondo and others 2006). More frequent and intense wildfires heighten the risk of runoff and erosion, particularly when followed by large episodic storms (Beeson and others 2001). The time sequence of post-fire land degradation in the Mediterranean tends to begin with a period of drought and a summer fire season, often followed by torrential rainfalls in the autumn (Moreno and others 1998), which can lead to significant degradation particularly on sensitive soils developed over limestones, sandstones and marls of eastern Spain (Cerdà 1998). Wildland fire and intense rainfall events can have a devastating impact on dryland watersheds and their capacity to be used sustainably (e.g. loss of productive top-soil, soil and sediment transport from burned areas into river systems and lakes, water management, flash floods and changing geomorphology). While post-fire precipitation can ultimately increase vegetation cover, there is frequently a lag period prior to vegetation regeneration where the land surface is exposed to potentially intensive rainfall events and subsequent run-off and soil erosion. Current land degradation risk modeling efforts often incorporate static maps of vegetation classes, climate, relief and soils, but omit the seasonal patterns of climate and vegetation growth. Incorporation of seasonal precipitation and vegetation growth dynamics will allow us to provide improved land degradation risk assessment maps and a tool to monitor vegetation and soil rehabilitation.

Remote sensing and geographic information systems (GIS) have been used extensively and effectively to assess fire behavior, the probability of wildland fire, post-fire effects, and ecological responses to fire (Lentile 2006). In Mediterranean systems, multi-temporal analysis of vegetation greenness, obtained through the Normalized Difference Vegetation Index (NDVI) has been used to assess temporal variations in factors associated with wildland fire. Satellite-derived NDVI has been particularly useful for assessing vegetation recovery (e.g., Viedma and others 1997, Diaz-Delgado and others 2002) and changes in fire regime (Malak and Pausas 2006). Image differencing (pre- and post-fire Landsat images) can provide a key input into erosion potential models which support the prioritization of post-fire interventions (e.g., Ruiz-Gallardo and others 2004, Perez-Cabello and others 2006). Landsat images have also been used for land degradation assessment, employing a wide spectrum of water erosion models (Vrieling 2006). Among those models are the universal soil loss equation (USLE) (Wischmeier and Smith 1978) and the revised USLE (RULSE) (Renard and others 1997), important management tools commonly used in agriculture and natural resource management. RUSLE has been adapted to spatially model watershed-scale erosion potential, using Landsat imagery as an input in assessing land cover (Millward and Mersey 1999, Miller and others 2003). In the RUSLE model, soil loss is highly sensitive to vegetation cover (Renard and Ferreira 1993), and as a result, efforts have been made to improve the geostatistical calculation of the C-Factor with Landsat imagery (Wang and others 2002).

Such efforts have primarily addressed the spatial variability in vegetation cover. However, they have generally not addressed the intra-annual temporal variability in vegetation cover. Though at relatively coarse spatial resolution (e.g., 1 km and 250 m), satellite imagery is acquired at very high temporal resolution by several sensors, and is used in wildfire and land degradation applications. For example, NDVI derived from higher temporal resolution imagery, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Justice and others 1998), is now regularly used to track fire and smoke in near real time (Kaufman and others 2003; Laneve and others 2006). It has also been used to map burned areas (Chuvieco 2005). These datasets have been less frequently applied to land degradation assessments, though a global erosion potential product has been developed (Yang and others 2003) using USGS Global Land Cover Characteristics Data Base in 1-km resolution (Loveland and others 2000).

The current research builds off of preliminary work by van Leeuwen and Sammons (2003, 2005), who began exploring the utility of integrating high temporal resolution NDVI data sets into soil loss and land degradation assessments through a multi-temporal derivation of the C-Factor used in RUSLE. The overarching goal of this research was to enhance our understanding of and ability to assess landscape vulnerability to wildfire. We endeavored to assess temporal vegetation dynamics influencing and reflecting landscape vulnerability to precipitation and wildfire in fire-prone dryland ecosystems and ultimately, predict post-fire soil erosion risk. Our research objectives were to evaluate the potential of using remote sensing data derived from high temporal resolution imagery (MODIS) to (1) assess post-fire plant cover dynamics, (2) improve soil loss model predictions for post-fire soil erosion dynamics, and (3) provide temporally dynamic means to assess landscape vulnerability to wildfires.

Study Areas

Three study areas were selected in eastern Spain (Fig. 1): Guadalest site, in Alicante, and Calderona and Millares sites in Valencia. The three sites represent common landscapes in Mediterranean drylands.

The Guadalest site was burned in 1998. Since then, plant cover has been monitored. Total area burned was about 200 hectares and included two main land uses: pine forest (covering ancient field crops) and scrubland (covering recently abandoned crops). The soils are fine-textured, developed over white marls and limestones. Steep slopes entirely structured in narrow crop terraces characterize the area, which is located at an elevation of 400-600 m. Mean annual precipitation is 658 mm (Guadalest reservoir station, 1972-2004 period) that falls mainly in autumn and winter.

The Millares site (about 140 km^2) is a complex of eleven watersheds that vary in their environmental conditions and potential vulnerability to wildfires. During the last 20 years, three large wildfires partially affected the area (1985, 1990 and 1994). Mean annual precipitation is 623 mm. Bedrock mainly consists of dolomite and limestone with some areas of marls and alluvial substrates. A number of small dams for flooding control are located along the drainage network in the area; these provided a set of eight watersheds for our investigation purposes. For every studied watershed, data on cumulative post-fire sediments produced from 1985 to 1997 were used as an indicator of watershed vulnerability to wildfires.

The Calderona site experienced a wildfire which burned about 700 ha of Aleppo pine (*Pinus halepensis*) forest on August 12, 2004. The soils in the area are coarse-textured. Stone cover in the study area is very high, typical of soils developed over sandstones. Mean annual rainfall is 500 mm, mostly occurring during autumn. Site monitoring started in June 2005, and included assessment of short-term dynamics of post-fire sediment yield at the micro-catchment scale.

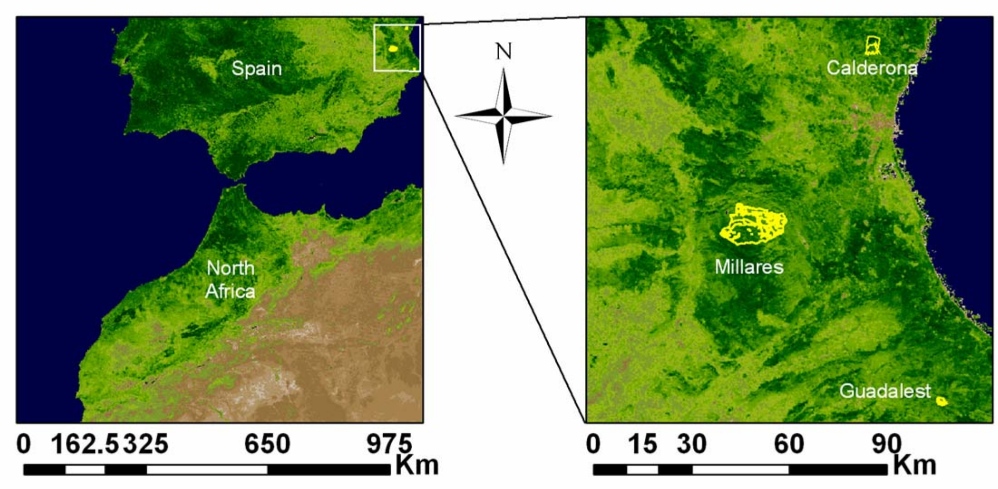

Figure 1— Study areas in Eastern Spain.

Methods

Vegetation Assessment from Multi-temporal NDVI Data

NDVI, which is positively correlated with the quantity of green biomass, has proven to be a useful measure of temporal vegetation dynamics because it is sufficiently stable to permit meaningful comparisons of seasonal and inter-annual changes in vegetation growth and activity (Tucker 1979, Myneni and others 1995). For this study, MODIS NDVI data from 2000 to the present were obtained for tiles covering the three study sites in eastern Spain. The specific product used was the 16-day composite NDVI at 250m resolution. These data were modified to formats that can be analyzed in a GIS.

The MODIS NDVI data were examined to help understand vegetation dynamics before and after wildfire. These analyses assisted in the development of a modified, spatially explicit RUSLE model and the assessment of vegetation regeneration patterns following wildfire. Although RUSLE is commonly used to assess annual soil loss, in this research the model is used to capture monthly land degradation risk. The RUSLE is an index method, which includes factors that represent how land cover, climate, soil, topography, and land use affect soil erosion caused by raindrop impact and surface runoff. These influences are described by the RUSLE (Wischmeier and Smith 1978, Renard and others, 1997) where average annual soil loss (A) is a function of:

$$A = K \times L \times S \times C \times R \quad (1)$$

(respectively, soil erodibility, slope length, slope steepness, cover-management, rainfall erosivity, and soil erosion prevention practice).

While the overall research addressed all RUSLE factors, here our focus is on the derivation of the C-Factor from multi-temporal MODIS-based NDVI. Wischmeier & Smith (1978) defined the C-factor as a ratio based on soil lost from a vegetated landscape relative to a standard of clean-tilled continuous-fallow conditions. High values of C-factor imply high erosion potential.

Since MODIS NDVI data are composited every 16 days, weighted average monthly images were created. The following formula was used to generate monthly C-factor surfaces from NDVI values (after van der Knijff and others 1999, 2000):

$$C=e^{(-\alpha\,((NDVI)/(\beta-NDVI)))} \qquad (2)$$

where α and β are unitless parameters that determine the shape of the curve relating NDVI and the C-factor. Van der Knijff (1999, 2000) found that this scaling approach gave better results than assuming a linear relationship. The C-factor has greater uncertainty for the lower range NDVI values due to non-photosynthetic vegetation (NPV) that is not measured by the NDVI as well as soil reflective properties. Prior application using MODIS data showed that an α of 2.5 and a β of 1 gave reasonable results (van Leeuwen 2003, 2005). A minimum NDVI threshold of 0.05 was set, below which it was assumed vegetation was absent (a C-factor of 1, or no ground cover). It is important to note that the C-factor values are a relative measure based on NDVI values and have not been calibrated.

Ground-based Assessment of Plant Cover and Soil Loss

Three different ground-based data sets – from the three sites studied – were used to evaluate the potential of multi-temporal NDVI data to assess landscape vulnerability to wildfires: plant-cover dynamics data from Guadalest site; short-term post-fire sediment yield from Calderona site; and long-term cumulative sediment yield from Millares site.

Post-fire vegetation cover dynamics in the Guadalest area was measured by the point intercept method (Greig-Smith 1983) in ten 50-m^2 plots, using a 0.5 x 0.5 m grid covering the entire plots. Total plant cover was measured 10, 20, 28, 34, 46, 57 and 70 months after the fire. The medium-term (6 post-fire years) data on vegetation cover dynamics in this site were used to perform comparative analysis between ground-based and MODIS data on vegetation dynamics.

To measure sediment yield in Calderona site, we selected five small catchments (average size about 0.2 ha) located on the burned area within the study site and placed silt-fences at the mouth of each catchment. Following each storm event, we measured and sampled sediments accumulated behind each silt fence. The monitoring system (silt-fences, rain gauges, etc.) was installed and fully operational by May 2005, eight months after the wildfire. Data on post-fire sediment yield from Calderona site were used for comparative analyses between ground-based sediment data and remotely sensed vegetation dynamics.

We used already available sediment-yield data to analyze the relative impact of wildfires on a set of 11 large watersheds in the Millares area. Post-fire sediment data were obtained by assessing cumulated sediments stored in a number of dams for flood control that were built in the area by the Regional Forest Service. For each watershed, the total volume of stored sediments was estimated by measuring sediment depth along cross sections in the dam sedimentation area, using large steel pins introduced vertically into the sediment until reaching the channel floor. Cumulative sediment data from Millares site were used to analyze the relationship between wildfire impact (measured as post-fire sediment yield) and long-term vegetation functional status after the wildfire (measured as MODIS-derived C-factor).

Results and Discussion

Vegetation assessment through MODIS data for the burned and unburned areas in the study sites showed both the important effect of seasonal variation and the strong impact of the wildfires on vegetation dynamics (Fig. 2). Two years after the Calderona wildfire, there was no clear sign of vegetation recovery. In Guadalest, the fire impact was still clear eight years after the wildfire, though differences between burned and unburned areas diminished with time and became smaller than seasonal variation. Both burned and unburned areas in Guadalest showed a decreasing trend in C-factor values, which could be related to the increasing trend in annual rainfall recorded during the study period (Mayor and others In Press).

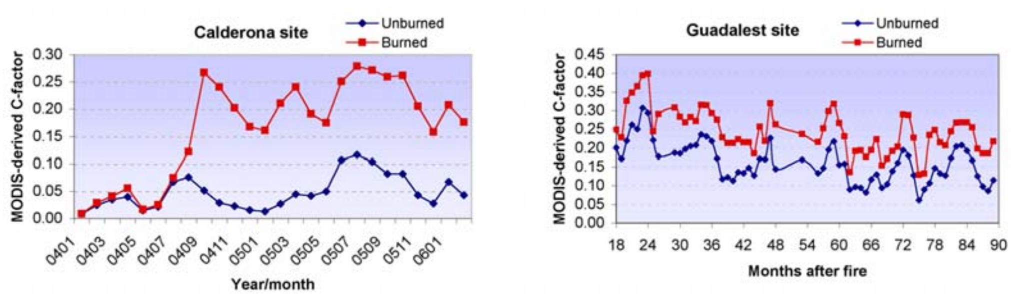

Figure 2— MODIS-derived C-Factor dynamics for burned and unburned pine forests in Calderona (August 2004 Wildfire) and Guadalest (August 1998 Wildfire) sites.

Peak values of the C-factor (and thus, higher erosion potential) occurred during the summer months, which are the driest months in the study sites. However, only part of the seasonal variation captured by the MODIS-derived C-factor would be expected to affect soil erosion. Thus, seasonal changes in canopy cover of evergreen sclerophyllous species and drought semi deciduous species may play a major role in soil erosion dynamics, while drought-related changes in the relative amount of plant biomass and necromass would not greatly modify soil erosion potential as they both protect the soil similarly. Canopy cover in Mediterranean drylands, such as the study sites, commonly decreases during summer, thereby increasing the soil vulnerability to fall rainstorms.

Comparisons made between MODIS-derived C-factor and ground-based soil cover data in the Guadalest site showed that MODIS-derived data captured well the post-fire trend of plant recovery and the related decreasing trend of bare soil cover (Fig. 3), though it seems that C-factor values underestimate the percent of bare soil at the highest bare-soil cover values.

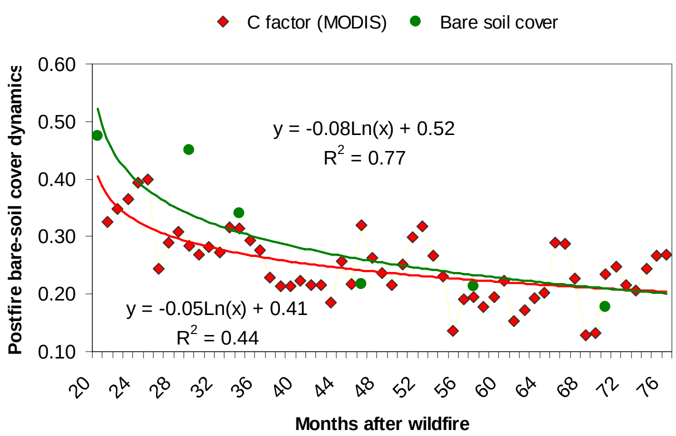

Figure 3— Post-fire Dynamics of Soil Cover and MODIS-C-Factor. Guadalest Site.

During the 18-month monitoring period in Calderona, nine sedimentation events were recorded. In general, post-fire sediment yield was low, and they were mostly produced by two heavy rainfall events. Once corrected by the erosivity of the rainfall (by dividing the amount of sediment by the modified Fournier index, MFI, Arnoldus 1978), sediment yield was exponentially related to MODIS-derived C-Factor (Fig. 4).

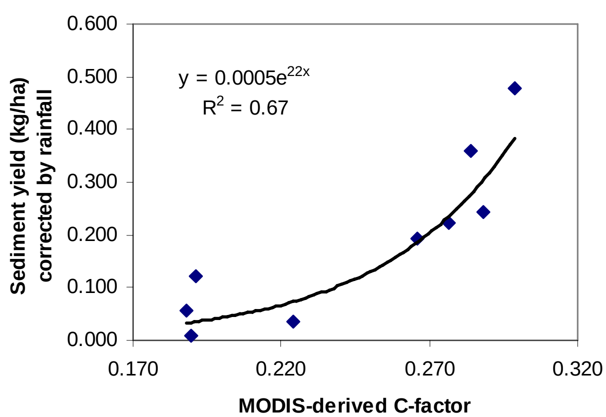

Figure 4— Relationship between MODIS-derived C-factor and sediment yield in Calderona site. Event-based sediment yield values were divided by the Modified Fournier's index ($MFI = Pi^2/Pa$; Pi = event precipitation, Pa= Annual precipitation).

Results from Guadalest and Calderona sites point out the potential of MODIS-derived C-Factor to capture post-fire short-term dynamics of plant recovery. The simple integration of rainfall and C-factor data appeared to be a valuable tool to estimate soil erosion.

On the other hand, more than six years after the last wildfire in the Millares area, there were consistent differences in MODIS-derived C-Factor values among the eight watersheds assessed. These differences were only barely masked by the seasonal variation (Fig. 5, left), and suggest a differential degree of plant recovery after the wildfires, which in turn could reflect a differential degree of vulnerability to wildfires. The co-variation between these long-term differences in C-Factor and the cumulated (from 1985 to1997) sediment yield produced after a number of previous wildfires in the area (Fig. 5, right) supports this interpretation.

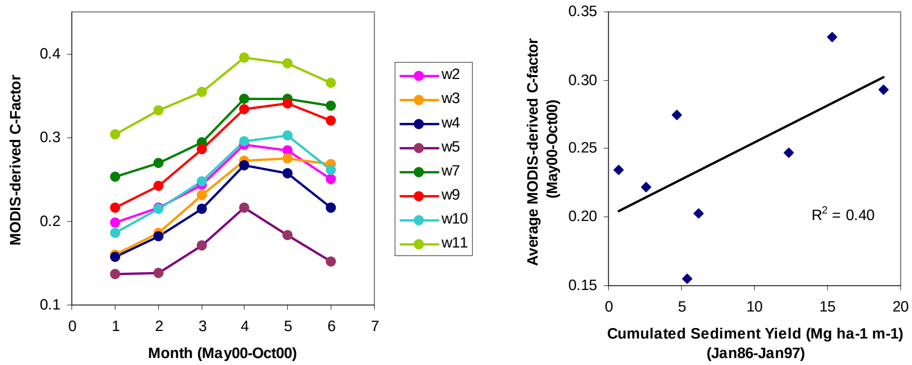

Figure 5—MODIS-derived C-factor dynamics (from May to October 2000) for the watersheds (w) in the Millares area (Left), and the relationship between the average C-factor values for the same period and the cumulated post-fire sediment yield in the respective watershed during the sediment monitoring period (1986-1987) (Right).

Our results point to the potential of the selected approach as a tool for rapid and cost-effective assessments of post-fire ecosystem recovery, which can be applied to large areas and used to analyze vulnerability factors at the regional scale. The assessment of land vulnerability to soil erosion at the regional scale is commonly based on conceptual factorial models that combine a number of vulnerability-related environmental factors to determine and map qualitative or semi-quantitative categories for erosion risk (Van der Knijff and others 2000, Gobin and others 2004). However, validation of predictions from those models is limited at the landscape scale, and validation approaches are commonly based on scattered data from small-scale monitoring field stations. Validation tools that can be applied to large spatial scales are lacking. Provided that remote sensing-derived vegetation data could be used to successfully estimate degradation and recovery trends of burned lands, further research will be focused on their potential as validation tools for post-fire vulnerability conceptual frameworks and models, and thus to facilitate further improvements.

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