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Using topographic and remotely sensed variables to assess ozone injury to conifers in the Sierra Nevada (USA) and Catalonia (Spain)

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ABSTRACT

The capacity to remotely identify impacts of ozone on conifers in California, USA and Catalonia, Spain was investigated using remote sensing and terrain-driven GIS analyses related to plant water relations and ozone uptake. The Ozone Injury Index (OII) field metric applied to *Pinus ponderosa* and *Pinus jeffreyi* in the USA and adapted to *Pinus uncinata* in Spain included visible chlorotic mottling, needle retention, needle length, and crown depth. Species classifications of AVIRIS and CASI hyperspectral imagery all approached 80% overall accuracy for the target bioindicator species. Remote sensing vegetation indices correlated best with longer-wavelength SWIR indices from the AVIRIS data in California, with the exception of the Photosynthetic Reflectance Index (PRI) correlation with the OII Visual Component (OII_{VI}), which was also the highest direct correlation in Catalonia. In Catalonia, the OII_{VI} alone and its subparts correlated better with the CASI data than with the full OII, namely the PRI ($R^2 = 0.28$, $p = 0.0044$ for OII_{VI}-amount and $R^2 = 0.33$ and $p = 0.0016$ for OII_{VI}-severity). Stepwise regression models of ozone injury developed using remote sensing indices combined with terrain-derived GIS variables were significant for OII in California ($R^2 = 0.59$, $p < 0.0001$) and in Catalonia ($R^2 = 0.68$, $p < 0.0001$ for OII_{VI}). Multiple regression models of ozone injury including a three year average of O_3 exposure were significant both with imaging spectroscopy indices alone ($R^2 = 0.56$, $p < 0.0001$) and with topographic variables added ($R^2 = 0.77$, $p < 0.0001$) in Catalonia. Applying the multivariate models to image classifications could provide useful maps useful for ozone impact monitoring but requires further validation before being considered operational.

1. Introduction

Ozone affects plant health through stomatal uptake (Matyssek et al., 2007; Panek, 2004), entering directly and oxidizing mesophyll cell membranes (Kickert & Krupa, 1990; Vollenweider, Ottinger, & Gunthardt-Goerg, 2002) resulting in chlorosis and decreased net photosynthesis (Arbaugh, Miller, Carroll, Takemoto, & Procter, 1998; Arbaugh et al., 2003; Ribas, Peñuelas, Elvira, & Gimeno, 2005a). Prolonged exposure also leads to accelerated leaf senescence (Pronos, Vogler, & Smith, 1978; Ribas et al., 2005a), growth reduction (Panek & Goldstein, 2001), changes in carbon allocation (Grulke & Balduman, 1999; Grulke, Preisler, Rose, Kirsch, & Balduman, 2002), and even changes in forest composition (Miller, 1973, 1993; Miller, Stolte, Duriscoe, Pronos, & technical coordinators, 1995). Research in Spain and the USA on ozone biomonitoring is moving towards improving metrics of ozone-specific injury symptoms for validating potential solutions to the variable ozone flux problem in Mediterranean climates (Alonso, Elvira, Sanz, Emberson, & Gimeno, 2007; Elvira, Alonso, & Gimeno, 2007; Inclan, Ribas, Peñuelas, & Gimeno, 1999; Kefauver, Peñuelas, & Ustin, 2012; Panek & Goldstein, 2001; Peñuelas, Ribas, Gimeno, & Filella, 1998). For example, ponderosa and Jeffrey pines (*Pinus ponderosa* Douglas ex. Laws; *Pinus jeffreyi* Grev. Balf.) have been used extensively as bioindicator species for ozone pollution in the western United States via the ozone injury index (Duriscoe, Stolte, & Pronos, 1996; www.fiaozone.net; Miller, 1993; Miller et al., 1995; Waring & Law, 2000). The Ozone Injury Index (OII) employs a weighted average of chlorotic mottling (OII_{VI}: 40%), needle whorl retention (OII_{RET}: 40%), needle length (OII_{LGT}: 10%), and crown death (OII_{CD}: 10%) to provide a reliable quantitative field metric (Duriscoe et al., 1996). The OII represents over 20 years of ozone biomonitoring research development in the Sierra Nevada Mountains (Duriscoe et al., 1996), and has proved to be similarly useful in application to the ozone-sensitive mountain pine in the Pyrenees of Catalonia (Kefauver et al., 2012).

A major obstacle in biomonitoring tropospheric ozone injury to forest health is scaling up from laboratory experiments and small plot field studies to landscape-scale studies (Karnosky et al., 2005; Kolb &

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Matyssek, 2001; Manning, 2005). This includes natural gradients in environmental conditions at the landscape scale that affect plant–water relations and thus stomatal uptake of ambient pollution levels (Panek & Goldstein, 2001; Peñuelas et al., 1998). This is of particular importance in semi-arid and Mediterranean climates where plant–water relations are a major limiting factor in ecosystem function and plants have adapted tolerance and avoidance mechanisms (Dallman, 1998). In addition, the seasonality of drought stress in Mediterranean climates leads to a large seasonal disconnect between tropospheric ozone and plant stomatal uptake, i.e. the flux timing problem (Matyssek et al., 2007). In turn, this seasonal disconnect of exposure and uptake further exacerbates the spatial variability component, resulting in an even larger variability of tropospheric injury to forest health in Mediterranean climates (Panek, 2004; Panek & Goldstein, 2001; Peñuelas et al., 1998; Ribas, Peñuelas, Elvira, & Gimeno, 2005b).

Tropospheric ozone concentrations in the California Sierra Nevada Mountains (W USA) and the Catalan Pyrenees (NE Spain) frequently surpass recommended air quality standards for human and environmental health (Finlayson-Pitts & Pitts, 1997; Hayhoe et al., 2004; Miller, 1993; Ribas & Peñuelas, 2003; Skarby, Ro-Poulsen, Wellburn, & Sheppard, 1998; Smith, Coulston, Jepsen, & Prichard, 2003). Historically, knowledge of the effects of high levels of tropospheric ozone concentrations on forest health was based on ambient concentrations, but this assumes a direct correlation between ozone concentration and plant uptake (Karnosky, Skelly, Percy, & Chappekla, 2007; Matyssek et al., 2007). Threshold-based ozone exposure assessments, such as the AOT40 standard, have been proven insufficient, specifically in Mediterranean climates (Filella, Penuelas, & Ribas, 2005; Fuhrer, Skarby, & Ashmore, 1997; Matyssek & Innes, 1999; Novak et al., 2002; Panek, 2004; Paoletti, 2006). As such, observation of ozone exposure alone is not sufficient to predict O_3 injury in Mediterranean-type climates and further work is warranted on approaches that account for plant–water relations in the application of ozone impact assessments at multiple scales (Matyssek et al., 2007; Paoletti, 2006).

The tools of GIS (geographical information system) and imaging spectroscopy enable extensive observational studies. Using terrain-driven analyses to estimate tree physiological condition and other environmental variables related to its position in the landscape (Urban, Miller, Halpin, & Stephenson, 2000) takes advantage of the natural gradients that affect ozone stomatal uptake to integrate environmental conditions with physiological measures of ozone injury. Many environmental parameters indirectly related to plant water availability, drought stress, evapotranspiration and thus ozone stomatal conductance are readily modeled using digital elevation model (DEM) data in a GIS, such as elevation, slope, aspect, topographic curvature (Zevenbergen & Thorne, 1987), topographic convergence (Beven & Kirkby, 1979) solar irradiance (Hofierka & Suri, 2002) and distance to water sources (Watson & Philip, 1985). Each terrain-related variable estimates environmental factors indirectly related to plant water usage (elevation, aspect, and solar irradiance) and availability (distance to water sources, slope, topographic curvature, and topographic convergence). We hypothesize that by including proxies related to both plant water usage and availability, an approximation of ozone stomatal conductance can be obtained via terrain-related variables alone.

Likewise, imaging spectroscopy provides a unique opportunity to bridge the gap between global monitoring and local investigative research (Field, Randerson, & Malmstrom, 1995) via the highly scalable techniques of image classification (Asner & Heidebrecht, 2002; Asner et al., 2008; Baulies & Pons, 1995) and plant biophysical health assessment (Blackburn, 2006; Peñuelas & Filella, 1998; Treitz & Howarth, 1999; Ustin, Roberts, Gamon, & Asner, 2004, Ustin et al., 2009). Species-level classification mapping of an individual bioindicator species is very important for the subsequent interpretation of the physiological health variability assessment of that bioindicator across environmental gradients. For example, physiological indices based in the visible and near-infrared can estimate plant pigment concentrations and photosynthetic efficiency relative to common ozone injury symptoms (Carter, 1998; Curran, Windham, & Gholz, 1995; Gamon, Peñuelas, & Field, 1992; Gamon & Surfus, 1999; Gitelson, Gritz, & Merzylak, 2003; Gitelson, Zur, Chivkunova, & Merzylak, 2002; Peñuelas, Filella, & Gamon, 1995; Tucker, 1979; Ustin et al., 2009). Other indices independently estimate water content at 970 nm and 1200 nm relative to plant water conditions (Clark & Roush, 1984; Gao, 1996; Penuelas, Filella, Biel, Serrano, & Save, 1993; Serrano, Ustin, Roberts, Gamon, & Peñuelas, 2000; Stimson, Breshears, Kefauver, & Ustin, 2005; Ustin et al., 1998).

Specific spectral signals have been correlated to similar tree physiological symptoms and increased tree mortality has been observed in the Catalan Pyrenees (Díaz-de-Quijano, Vollenweider, Ogaya, & Peñuelas, 2011a; Ribas & Peñuelas, 2003; Ribas et al., 2005a). In particular, the mountain pine (*Pinus uncinata* Ram.) exhibits specific visual symptoms related to foliar ozone injury that have been verified microscopically (Díaz-de-Quijano, Peñuelas, Menard, & Vollenweider, 2011b; Vollenweider et al., 2002). Recent research has also shown that ozone damages plant pigment concentrations in ways that allow identifying ozone injury from other sources of stress (Di Vittorio, 2009). However, such a minute pigment-based signal has so far only proven measurable with needle level lab and field spectroscopy (Di Vittorio & Biging, 2010; Ustin & Curtiss, 1990), though it could potentially be within the reach of next-gen imaging spectroscopy platforms. Such analyses are promising with increasing airborne and satellite sensor signal strength, but the more general indices related of the decline to overall tree health due to prolonged exposure may still provide adequate information for more general ozone injury assessments when placed in a landscape context.

In this paper, we present two case studies of an integrative technique combining terrain-based spatial analyses and imaging spectroscopy for landscape scale analyses of the impact of tropospheric ozone on forest bioindicator species' health. The first objective of this research was to develop a reliable technique for species level classifications of mixed forests from hyperspectral imagery data in order to allow for analyses of a single bioindicator species sensitive to tropospheric ozone. Our second objective was then to investigate the use of imaging spectroscopy of bioindicator species' health, specific pigment concentrations, and photosynthetic efficiency related to damage caused by tropospheric ozone. Improvements in the application of imaging spectroscopy specifically for assessing ozone injury to bioindicator plant health in Mediterranean climates were then investigated using topographic variables as proxies of plant water relations in order to account for environmental and seasonal variability and bridge the gap between ozone exposure and ozone stomatal uptake. Relationships between terrain-driven environmental variables related to plant water status, imaging spectroscopy of forest biophysical condition, and ozone exposure were then employed to develop meaningful and ecologically relevant models for assessing tropospheric ozone injury to forest health.

2. Study site characteristics

Yosemite National Park (YOSE) and Sequoia-Kings Canyon National Park (SEKI) are located in the Central Sierra Nevada Mountain Range in California (Fig. 1). Both parks feature large glacial carved granitic valleys ranging from approximately 1200 m to 2400 m in elevation. Similar climates and substrates are reflected in similar vegetation dominated by ponderosa and Jeffery pine mixed mainly with incense cedar (*Calocedrus decurrens* (Torr.) Florin), white fir (*Abies concolor*), California black oak (*Quercus kelloggii* Newb.), and canyon live oak (*Quercus chrysolepis* Liebm.). At higher elevations and shallower soils, ponderosa pine is replaced by the morphologically similar Jeffery pine. Both valleys have central rivers that support mesic habitats with little summer drought stress compared to the much drier xeric conditions upslope.

The two perpendicular transects of “Guils” (E–W) and “Meranges” (N–S) in Catalonia, Spain include similar elevation ranges, intersecting