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Effects of grazing on leaf area index, fractional cover and evapotranspiration by a desert phreatophyte community at a former uranium mill site on the Colorado Plateau

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ABSTRACT

This study employed ground and remote sensing methods to monitor the effects of grazing on leaf area index (LAI), fractional cover (f_c) and evapotranspiration (ET) of a desert phreatophyte community over an 11 year period at a former uranium mill site on the Colorado Plateau, U.S. Nitrate, ammonium and sulfate are migrating away from the mill site in a shallow alluvial aquifer. The phreatophyte community, consisting of *Atriplex canescens* (ATCA) and *Sarcobatus vermiculatus* (SAVE) shrubs, intercepts groundwater and could potentially slow the movement of the contaminant plume through evapotranspiration (ET). However, the site has been heavily grazed by livestock, reducing plant cover and LAI. We used livestock exclosures and revegetation plots to determine the effects of grazing on LAI, f_c and ET, then projected the findings over the whole site using multi-platform remote sensing methods. We show that ET is approximately equal to annual precipitation at the site, but when ATCA and SAVE are protected from grazing they can develop high f_c and LAI values, and ET can exceed annual precipitation, with the excess coming from groundwater discharge. Therefore, control of grazing could be an effective method to slow migration of contaminants at this and similar sites in the western U.S.

1. Introduction

1.1. Importance of phreatophyte shrub communities

Phreatophyte shrub communities cover tens of millions of hectares of arid and semiarid rangeland in the intermountain basins of the western U.S. (Shreve, 1942). They access aquifers to depths of 8 m or greater, and are important components of the regional water balance in these areas (Naumber et al., 2005; Nichols, 1993, 1994, 2000; Steinwand et al., 2006). When protected from grazing they can develop dense ground covers (McKeon et al., 2006) with high evapotranspiration (ET) rates (Glenn et al., 2009). They can consume more water than arrives as precipitation, with the excess supplied by groundwater derived from mountain recharge or other sources (Groeneveld et al., 2007). On the other hand, many western rangelands have a history of heavy grazing by sheep and cattle, which can greatly reduce shrub ground cover and leaf area index (LAI) (Pellant et al., 2004; Redsteer et al., 2010). This can tip the water balance from discharge to recharge and runoff, potentially leading to formation of gullies and other forms of erosion (Pellant et al., 2004). Land managers are challenged to understand the interactions between vegetation, land use patterns and the regional water cycle in phreatophyte-dominated arid areas, and to develop methods to monitor components of the water balance over large landscape areas and long time scales in sparse vegetation communities (Naumber et al., 2005; Pellant et al., 2004).

1.2. Background of the present study

This study used ground and remote sensing methods to assess the contribution of native shrubs to the water balance over an 11-year period at a desert site near Monument Valley, Arizona, on the Colorado Plateau (U.S. Department of Energy, 1999). The site is located on the Navajo Nation and was a former uranium-milling site, abandoned in 1968. Nitrate, ammonium and sulfate, used in the extraction of uranium from the ore, are migrating away from the source area in a contamination plume in the shallow alluvial aquifer. The two dominant shrubs at the site are *Sarcobatus vermiculatus* (SAVE) and *Atriplex canescens* (ATCA) (Chenopodiaceae),

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both of which extract water from the deep vadose zone as well as the alluvial aquifer (McKeon et al., 2006; Jordan et al., 2008). Our working hypothesis was that a healthy plant community protected from grazing could reduce the movement of the contaminant plume through ET.

1.3. Grazing reduction during the study period

The Navajo Nation has historically been over-grazed (Pellant et al., 2004; Redsteer et al., 2010). However, it underwent a marked reduction in grazing pressure during the study period in response to a regional drought that extended from 1999 to 2009 (Redsteer et al., 2010). Near the beginning of the drought in 2001, the range was stocked with an estimated 41% more animals than were authorized by permits (Navajo Nation Department of Water Resources, 2003). This led to a mass die-off of livestock during the drought; Navajo officials reported that 30,000 cattle perished from 2001 to 2002, approximately 50% of the total population (Redsteer et al., 2010). In 2003 the Navajo Nation Department of Water Resources issued a drought contingency plan that called for ranchers to sell livestock to reduce herd size to what could be supported under the existing drought conditions (Navajo Nation Department of Water Resources, 2003). Although accurate statistics are not available because animal-inventory reporting is voluntary on the Navajo Nation, livestock numbers are estimated to have been reduced by at least 50% over the course of the drought, from approximately 403,000 sheep units in 2001 (Navajo Nation Deparment of Water Resources, 2003), to 200,000 in 2007 (where one cattle unit = 4 sheep units).

Observations at our site showed it was heavily grazed from 2000 to 2004, and less heavily grazed from 2005 to 2010, presenting a contrast in grazing pressure over years (McKeon et al., 2005; Jordan et al., 2008; Glenn et al., 2009).

1.4. Objectives

The present study had two objectives: develop ground-calibrated satellite methods to monitor LAI, fractional vegetation cover (f_c) and ET over relevant spatial and temporal scales based on satellite vegetation indices (VI); and to use these methods to evaluate the effects of ATCA and SAVE on the local water balance, as affected by site remediation efforts and reduced grazing pressure. The study build on previous revegetation and grazing protection pilot projects conducted at the site (McKeon et al., 2005, 2006; Jordan et al., 2008; Glenn et al., 2009).

1.5. Application of remote sensing to arid zone vegetation studies

Due to the clumped nature of arid-zone shrubs, shadow effects, and large areas of bare soil between shrubs, the relationship between satellite-derived VIs and biophysical properties of vegetation can be non-linear (Huete et al., 1992; Ray and Murray, 1996). Williamson (1989) measured reflectances from shrubs growing over different soil types in a sparsely vegetated area of South Australia and concluded that soil type significantly affected reflectance values of mixed scenes (see also Pickup et al., 1993). White et al. (2000) compared different ground methods for estimating f_c and LAI in the Chihuahuan Desert, and concluded that routine monitoring of plant area index (leaves plus stems) and f_c was feasible, but that green LAI was more problematic. Further, they concluded that differences in canopy structure and soil properties require that the appropriate variables to be measured and the measuring instruments must be site-specific.

Salz et al. (1999) used Landsat 5 imagery to attempt to detect grazing effects at a hyper-arid rangeland in Israel. Ground measurements showed a 30% reduction in vegetation cover at grazed sites compared to un-grazed sites, a difference with ecological and management significance. However, the drop in actual vegetation cover, from 15.8% in un-grazed plots to 11.2% in grazed plots, was too small to be detected by the five VIs tested in the study. They concluded that satellite imagery cannot serve as a direct index of plant cover in hyper-arid areas. Groeneveld et al. (2007) found that VI-based remote sensing methods could accurately estimate desert phreatophyte ET at moderate or high rates, but in sparse plant stands Root Mean Square Errors were as high as 40% compared to moisture flux tower data. This calls into question the feasibility of estimating ET by remote sensing in sparse desert plant communities.

On the other hand, Smith et al. (1990) showed that TM imagery could predict vegetation cover across different soil types and over different sampling dates in a study in the Mojave Desert, and that remote sensing estimates could in some respects be more accurate than ground survey methods. Peters and Eve (1995) found that even coarse-resolution satellite imagery could be used to monitor vegetation growth patterns and response to rainfall in arid regions. Nagler et al. (2007) found that satellite vegetation indices could accurately reproduce ET values measured by moisture flux towers in semi-arid shrub and grass plots. Hence, the value of remote sensing for monitoring vegetation and ET in sparse desert settings is uncertain, and appears to be site-specific.

In this study we used high-resolution Quickbird imagery to establish relationships between f_c and LAI measured on the ground with satellite panchromatic (black and white) and NDVI imagery, respectively. This was possible because individual shrubs are visible on Quickbird imagery for comparison with ground measurements. We then used Landsat 5 imagery to project results over longer time scales, by inter-calibrating Quickbird and Landsat NDVI values using common scenes on the images. Finally, we used the Enhanced Vegetation Index (EVI) on the Moderate Resolution Imaging Spectrometer (MODIS) on the Terra satellite to project annual cycles of ET over the site as affected by grazing pressure, precipitation and remediation efforts, using algorithms developed previously to scale ground measurements of ET by sap flux sensors to larger landscape units and longer time spans at the site (Glenn et al., 2009). These results were used to model ET as a function of precipitation and grazing pressure, and they were compared to ET estimates from the new MODIS MOD16A2 ET product (Mu et al., 2011).

2. Methods

2.1. Site history

The Monument Valley Uranium Mill Tailing Remedial Action (UMTRACA) site occupies about 230 ha in Cane Valley, Arizona (Fig. 1) (U.S. Department of Energy, 1999). It is a high desert environment on the Colorado Plateau of the Great Basin Province of North America. Average annual precipitation is 150 mm yr^{-1}. Uranium mining at the site occurred from 1943 to 1968 (U.S. Department of Energy, 1999). From 1964 to 1968 sulfuric acid (H_2SO_4) was used to leach uranium out of ore and ammonium nitrate (NH_4NO_3) and calcium oxide (CaO) were used to precipitate uranium out of solution as a solid oxide. Residual tailings and spent leaching solutions were placed on site in several unlined piles. In 1992, the U.S. Department of Energy, in conjunction with the Navajo Nation, began removing the tailings. This surface remediation initiative was completed in 1994. Tailings were hauled to a new site where they were capped with an engineered radon barrier, and radioactive materials in the topsoil were removed until the surface soil was below levels of concern for radionuclides (U.S. Department of Energy, 1999). Further investigations revealed that nitrate,