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Quantifying plant-soil-nutrient dynamics in rangelands: Fusion of UAV hyperspectral-LiDAR, UAV multispectral-photogrammetry, and ground-based LiDAR-digital photography in a shrub-encroached desert grassland

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Rangelands cover 70% of the world's land surface, and provide critical ecosystem services of primary production, soil carbon storage, and nutrient cycling. These ecosystem services are governed by very fine-scale spatial patterning of soil carbon, nutrients, and plant species at the centimeter-to-meter scales, a phenomenon known as "islands of fertility". Such fine-scale dynamics are challenging to detect with most satellite and manned airborne platforms. Remote sensing from unmanned aerial vehicles (UAVs) provides an alternative option for detecting fine-scale soil nutrient and plant species changes in rangelands over smaller extents than typically imaged with satellite and manned airborne platforms. We demonstrate that a model incorporating the fusion of UAV multispectral and structure-from-motion photogrammetry classifies plant functional types and bare soil cover with an overall accuracy of 95% in rangelands degraded by shrub encroachment and disturbed by fire. We further demonstrate that employing UAV hyperspectral and LiDAR (light detection and ranging) fusion greatly improves upon these results by classifying 9 different plant species and soil fertility microsite types (SFMT) with an overall accuracy of 87%. Creosote bush (*Larrea tridentata*) and black grama (*Bouteloua eriopoda*) are the most important native species in the rangeland and have the highest producer's accuracies at 98% and 94%, respectively. The integration of UAV LiDAR-derived plant height differences was critical in these improvements. Finally, we use synthesis of the UAV datasets with ground-based LiDAR surveys and lab characterization of soils to estimate that the burned rangeland potentially lost 1,474 kg/ha of C and 113 kg/ha of N owing to soil erosion processes during the first year after a prescribed fire. However, during the second-year post-fire, grass and plant-interspace SFMT functioned as net sinks for sediment and nutrients and gained approximately 175 kg/ha C and 14 kg/ha N, combined. These results provide important site-specific insight that is relevant to the 423

Mha of grasslands and shrublands that are burned globally each year. While fire, and specifically post-fire erosion, can degrade some rangelands, post-fire plant-soil-nutrient dynamics might provide a competitive advantage to grasses in rangelands degraded by shrub encroachment. These novel UAV and ground-based LiDAR remote sensing approaches thus provide important details towards more accurate accounting of the carbon and nutrients in the soil surface of rangelands.