COMPARING DYNAMICS OF MIXED-CONIFER WOODLANDS ON THE BANDERA LAVA FLOW, NEW MEXICO

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ABSTRACT—We hypothesized that vegetative changes would be visible in a series of repeat photographs (1948–2010) taken at the edge of the Bandera Lava Flow, New Mexico, while inventory of trees and data on age would reveal minimal structural and compositional changes at a woodland site on the inaccessible interior of the lava flow. We concluded that the insular qualities of the volcanic badlands resulted in minimal changes at the interior site during the twentieth and early twenty-first centuries, while noticeable vegetative changes occurred at the periphery of the Bandera Lava Flow during the same period. Vegetative changes at the lava-substrate interface could be linked to variability in use of land, management of fire, and precipitation.

RESUMEN—Hipotetizamos que los cambios de vegetación serían visibles en una serie de fotografías de repetición (1948–2010) sacadas en el borde del flujo de lava Bandera, Nuevo México, mientras que un inventario de árboles y datos de edad revelarían cambios mínimos de la estructura y la composición en un sitio boscoso en el interior inaccesible del flujo de lava. Concluimos que las cualidades insulares de las tierras volcánicas siguieron a cambios mínimos en el lugar interior durante los siglos 20 y principios del 21, mientras que cambios vegetales notables ocurrieron en la periferia del flujo de lava Bandera durante el mismo período. Cambios vegetales en la interfaz de lava y suelo podrían estar relacionados con la variabilidad del uso de tierra, manejo de fuego y la precipitación.

Numerous studies have analyzed repeat historical photographs to provide evidence of environmental and anthropogenic changes to western landscapes (Hastings and Turner, 1965; Veblen and Lorenz, 1991; Allen et al., 1998; Butler and DeChano, 2001; Noel and Fielder, 2001; Hutchinson, 2000; Turner et al., 2003; Elliott and Baker, 2004; Griffin et al., 2005; Zier and Baker, 2006). Repeat-photography (rephotography) analysis compares two or more photographs, depicting the same subject, captured at specified times (Rogers et al., 1984). Although not as spatially comprehensive as aerial photographs and satellite imagery, repeated ground-based photographs provide finer scale for assessment of vegetative changes and anthropogenic activity. Ground-based photography also predates remotely sensed data in many locations (Turner et al., 2003). Repeat historical photographs provide a visual assessment of environmental effects on establishment, growth, and mortality of trees. Rephotography also may permit unique analyses and inferences, especially regarding fragmentation of vegetation, morphological changes in plants, species-composition, and structure of stands. The drought of the early 2000s and projections of regional drying through the remainder of the twenty-first century (Seager et al., 2007; Hughes and Diaz, 2008) raise questions concerning the future effects of climatic change in ecosystems of the Southwest (Baron et al., 2009). Existing studies suggest that the ongoing global-change type of drought has already increased rates of mortality in some southwestern species of conifers (Breshears et al., 2005; Allen et al., 2010; Williams et al., 2012). Additional studies present conflicting results regarding the persistence of *Populus tremuloides Michx.* in western North America during recent decades (Kay, 1997; Manier and Laven, 2002; Elliott and Baker, 2004; Kulakowski et al., 2004).

Mixed-conifer woodlands cover much of the lava flows at El Malpais National Monument (El Malpais), New Mexico. The basalt abruptly transitions into a surrounding substrate that supports a community of grasses, shrubs, and trees (Bleakly, 1997). Previous studies showed that many trees growing on the Quaternary Period lava flows at El Malpais live to very old ages, suggesting that the volcanic badlands insulate vegetation from negative environmental impacts (i.e., drought and anthropogenic activity). Research by Grissino-Mayer (1995; 1996) identified hundreds of ancient conifers and pieces of remnant wood on the basalt formations at El Malpais. His findings suggested that disturbances (natural and anthropogenic) of the ecosystem and subsequent vegetative changes occur infrequently on

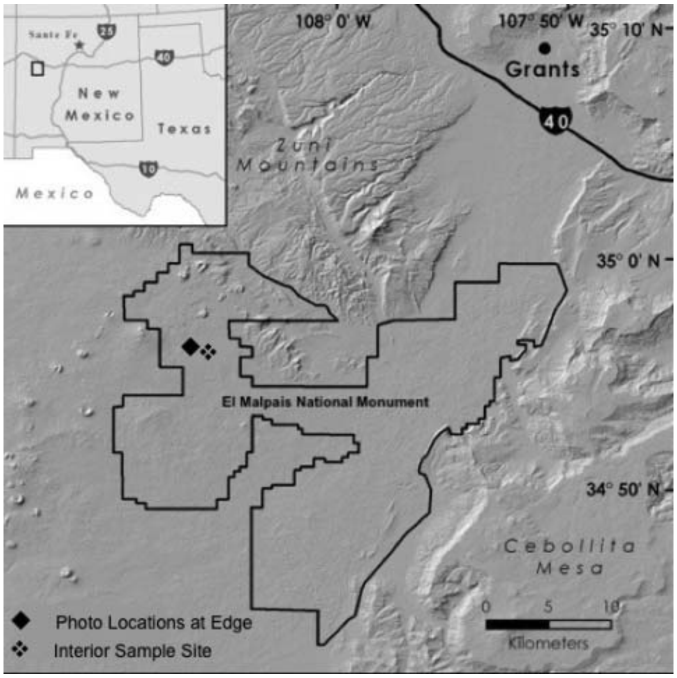

Fig. 1—Study area at El Malpais National Monument (black polygon) in New Mexico. Black diamond = approximate location of sites of repeat-photography along the edge of the Bandera Lava Flow near Big Tubes. Black and white diamond = approximate location of 0.5-ha sample-plot on the interior of the Bandera Lava Flow.

the interior of the rugged lava flows. However, much of the land surrounding the basalt formations was heavily impacted by industrial logging and grazing during the late nineteenth and early twentieth centuries (Mangum, 1997). The stark contrast in characteristics of sites at El Malpais provides the opportunity to investigate fine-scale vegetative dynamics at two land-use and ecological extremes: the lava interior, which is difficult to access and is moisture retentive; the lava edge, which is more accessible but drier than the interior.

Lindsey (1951) initiated rephotographic research in the area during the 1940s by producing a collection of photographs that detailed the flora and geology of El Malpais. A. A. Lindsey repeated many of his photographs during the summer of 1981. He noticed changes in some scenes, while other subjects remained essentially the same (Lindsey, 1997). Our objective was to augment the work of Lindsey (1997) by photographing a selection of the scenes a third time during summer 2010. The goals of our study were to assess vegetative dynamics in historical and contemporary photographs taken at the lava-substrate interface, investigate the dynamics of woodland stands on the protected interior of a lava flow; and compare dynamics of contemporaneous vegetation at the two locations. We hypothesized that vegetative changes would be apparent at the lava-substrate interface, while minimal changes would be detected at our sample site on the lava interior.

Materials and Methods—Our study was conducted at El Malpais, which was established 31 December 1987 (Mangum, 1990; Fig. 1). The monument is located on the Datil Section of the Colorado Plateau, which stretches across parts of west-central New Mexico and east-central Arizona. Elevations at El Malpais range from 1,950–2,400 m. The Köppen Climate Classification System categorizes much of the region as a hot steppe (BSh). Local weather is characterized by hot summers (average maximum July temperature >30°C), cold winters (average minimum January temperature less than −10°C), and relatively low precipitation. Average annual precipitation at El Malpais is ca. 400 mm, much of which can be attributed to winter precipitation and the summer rains that accompany the North American Monsoon (Sheppard et al., 2002; Lewis, 2003; Stahle et al., 2009*a*). The Zuni-Bandera volcanic field is the most prominent feature of the landscape at El Malpais. Thousands of hectares of El Malpais and surrounding areas are covered with undulating basalt formations deposited during the Quaternary Period (Laughlin et al., 1993; Laughlin and Wolde-Gabriel, 1997). One of the major basalt features at El Malpais is the Bandera Lava Flow which originates from Bandera Crater and extends along the western boundary of El Malpais. Radiometric dating indicates that the Bandera Lava Flow was deposited during eruptions that occurred between 10,000 and 11,000 years before present (Laughlin and Wolde-Gabriel, 1997).

The basalt flows and volcanic craters at El Malpais support a patchwork of shrubs, herbs, and grasses. El Malpais also harbors one of the best-preserved old-growth woodlands in the western United States (Grissino-Mayer, 1995; Grissino-Mayer et al., 1997; Lewis, 2003). The old-growth woodlands at the site are primarily composed of mixed-conifers. Dominant species of trees are *Pseudotsuga menziesii* (Mirb.) Franco, *Pinus ponderosa* Douglas ex C. Lawson, *Juniperus scopulorum* Sarg., *Juniperus monosperma* Engelm., and *Pinus edulis* Engelm. Small populations of *P. tremuloides* also are present on some basalt formations. Trees growing on lava flows within El Malpais are primarily noncommercial specimens characterized by irregularly-shaped stems, sparsely-foliated crowns, and other diagnostic features of old-growth (Schulman, 1954; Stahle and Chaney, 1994; Grissino-Mayer et al., 1997). The highly-fractured basalt effectively stores surface run-off like a sponge, allowing deep-rooted conifers to endure sustained periods of minimal precipitation (Shields and Crispin, 1956; Grissino-Mayer, 1995). Therefore, the lava flows often exhibit more species of trees and greater stem-density than the weathered basalt and sedimentary rock that form the surrounding substrate (Bleakly, 1997). Poor timber-quality and the inhospitable terrain serve as deterrents to anthropogenic disturbances on the lava flows (e.g., grazing by livestock and logging), allowing many conifers to live for centuries. Trees growing on the lava flows also are more protected from natural phenomena (e.g., wildfires and pathogens) due to the isolating effects of life on the basalt (Grissino-Mayer and Swetnam, 1997; Lewis, 2003).

We examined historical photographs, taken by A. A. Lindsey, of ecological communities and geologic formations on the volcanic badlands in and around El Malpais NM. The images are archived at the headquarters of El Malpais NM in Grants, New Mexico, as black and white photographic plates 10.60 × 15.24 cm. The collection consists of initial photographs paired with subsequently repeated images of the same scenes photographed >30 years later. The first set of photographs was taken during the summers of 1947 and 1948, while the repeated set was produced during the summer of 1981. Notes that A. A. Lindsey prepared for an unpublished report to the Bureau of Land Management in 1981 accompany the photographs. We chose to work with two rephotographed scenes that showed conditions at the edge of the Bandera Lava Flow in an area of El Malpais NM known as the Big Tubes. The images we selected were among the few in the collection of A. A. Lindsey that featured distinguishable vegetation at the lava-substrate interface. The photographs showed adjacent locations with an ca. 0.5-ha combined field of view.

Historical photographs used in this study were digitized in grayscale at 236 dots/cm, cropped for uniformity, and saved as TIFF (Tagged Image File Format) files (Griffin et al., 2005). We produced a third photograph of the selected scenes on 10 August 2010. The new images were produced with a hand-held, digital single-lens reflex camera at a focal length of ca. 55 mm and a cropping factor of 1.6x. Camera location and azimuth were recorded with a GPS (Global Positioning System) receiver and a digital compass. Digital images were saved as JPEG (Joint Photographic Experts Group) files, which were later cropped and edited with Adobe Photoshop (Adobe Systems Incorporated, San Jose, California). The 2010 pictures completed a three-part, >60-year visualization of the dynamics of vegetation along this section of the lava edge. We visually identified changes in structure and composition of the stand among the photographs to chronicle twentieth-century woodland-dynamics at the margin of the Bandera Lava Flow. Horizontal scans across the images were performed with the digital loupe tool (2x magnification) included with Apple Aperture computer software (Apple Inc., Cupertino, California). We specifically searched for evidence of mortality and regeneration of trees, changes to composition of species of trees, and changes to groundcover. Changes among the photographs were listed and collectively analyzed as a visual time series of vegetative dynamics at the boundary between the Bandera Lava Flow and the surrounding substrate.

Data on structure of woodland were collected at a 0.5-ha rectangular plot to provide comparisons between rephotography sequences taken at the periphery of the Bandera Lava Flow and observations from a comparably sized area on the interior of the lava (Fig. 2a). The 0.5-ha plot was established 0.71 km southeast of the locations of cameras at Big Tubes. A large area of fractured, uneven basalt with minimal vegetation (i.e., no trees) extended east of the lava edge (Fig. 2b), which prevented us from establishing the interior plot closer to the locations of cameras at Big Tubes. All living trees within the plot ≥10 cm in diameter at ground level (D_{GL}) were identified to species, inventoried, and cored with an increment borer. Dead trees were identified and photographed. Additional attention was directed to recording the presence of tree saplings and other groundcover. Tree-ring specimens were mounted, sanded (Orvis and Grissino-Mayer, 2002), and aged using standard dendrochronological methods (Yamaguchi, 1991). Age-data from the plot were used to quantify stand-dynamics at the interior location using observation-intervals that matched our three-part rephotography sequences.

Results—Vegetative changes were apparent in the rephotography sequences produced at the edge of the Bandera Lava Flow. Several *P. ponderosa* that appeared alive in the 1948 images were dead in later photographs, while a prominent *P. ponderosa* in the foreground matured during the same period and appeared healthy in 2010 (Fig. 3a). The 1981 photographs recorded the emergence of *P. tremuloides* that we found dead in 2010. Multiple conifers persisted through the entire rephotography period, including *J. scopulorum*, *P. edulis*, and the old-growth *P. ponderosa* at the southern margin of the photographed sites (Fig. 3b). The rephotography sequences also showed increased vegetative cover in the foreground of the images. Continuous grass cover replaced the patchy substrate groundcover visible in earlier images prior to 2010.

Although the mixed-conifer woodland on the lava interior experienced some changes between 1948 and 2009, the dynamics appeared to be less pronounced than those observed at the lava-substrate interface. Drought-tolerant conifers within the interior plot were larger and displayed more old-growth features (e.g., twisted stems, strip bark, and spiked tops; Stahle and Chaney, 1994; Grissino-Mayer et al., 1997) than those at the lava edge. Aging the trees within our interior plot allowed us to determine which of the 80 stems identified as ≥10 cm in D_{GL} during 2009 persisted throughout the period included in our rephotography sequence. Only 9 of the 80 trees (11%) in our plot that were ≥10 cm in D_{GL} during 2009 established after 1948 (Table 1). In fact, many of the trees growing within the plot were >300 years old. We also identified three standing dead trees in the plot (two *P. ponderosa* and one *J. scopulorum*) and two downed dead trees (both *P. ponderosa*). Tree-seedlings were almost non-existent within the 0.5-ha plot. We identified six seedlings (three *P. edulis* and three *P. ponderosa*) as well as a coppice of stems of young *P. tremuloides*. We observed one dead, lightning-struck *P. ponderosa* at the site surrounded by living, unburned trees.

Discussion—Vegetative changes visible in our rephotography sequences correspond with regional variability in moisture during the past century (Fig. 4). Initial photographs were taken by A. A. Lindsey following the Dust Bowl Drought of the 1930s and at the beginning of the 1950s Drought, which was one of the worst droughts in western New Mexico in >1,000 years (Grissino-Mayer et al., 1997; Stahle et al., 2009*a*). The earliest pictures in our rephotography sequences do not show *P. tremuloides* growing at the lava edge. This species is not as drought-tolerant as the species of conifers that inhabit the woodlands at El Malpais NM (Burns and Honkala, 1990). The absence of *P. tremuloides* in the 1948 photographs could be the result of lower availability of moisture at the lava-substrate interface during that time due to the historic droughts of the early twentieth century. Establishment of *P. tremuloides* at the edge of the Bandera Lava Flow prior to the 1981 photographs

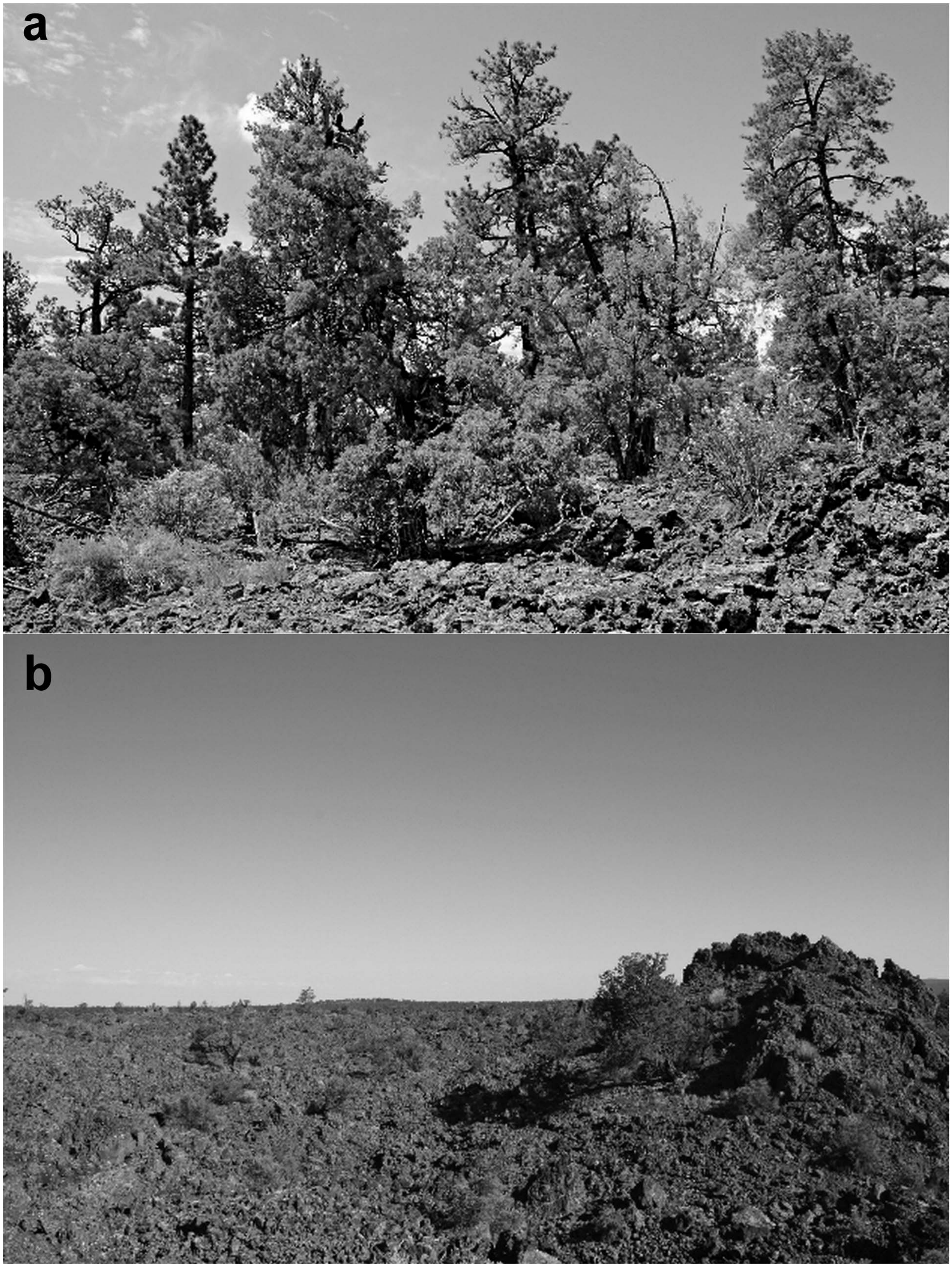

Fig. 2—a) Photograph showing a portion of the sampled plot located on the interior of the Bandera Lava Flow, New Mexico. b) Photograph showing the broad section of highly-fractured basalt on the Bandera Lava Flow between the photographed sites (near Big Tubes) at the lava edge and the 0.5-ha sampled plot on the lava interior.

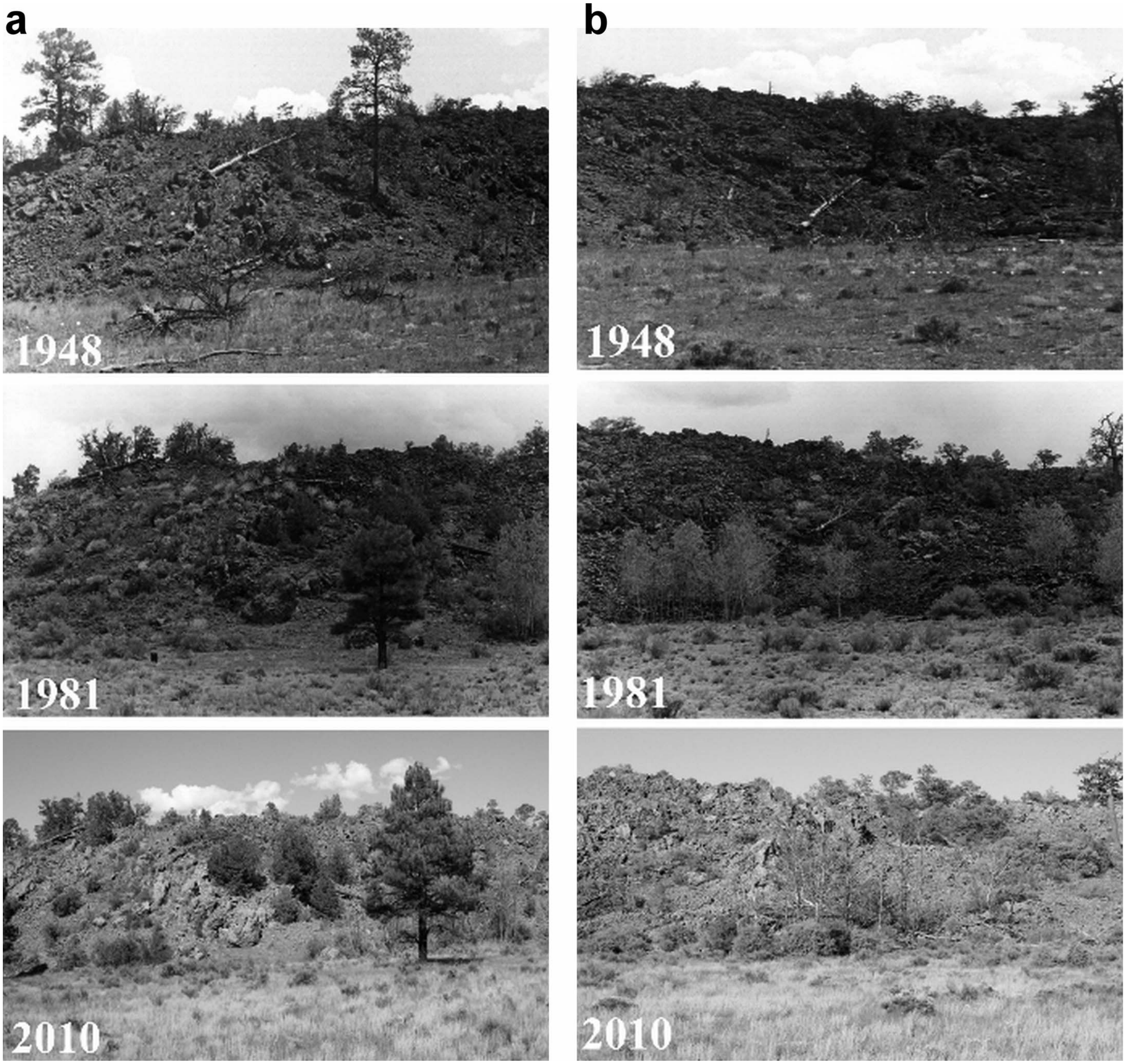

Fig. 3—Photographic sequences of sites in New Mexico. a) Edge of the Bandera Lava Flow near Big Tubes (34°57′28.0″N, 108°6′52.5″W; camera facing northeast at ca. 65°). b) Area adjacent (south) to site at edge of the Bandera Lava Flow near Big Tubes (34°57′27.9″N, 108°6′52.5″W; camera facing northeast at ca. 70°).

might be linked to increased precipitation during preceding years (Grissino-Mayer, 1995). The same individuals of *P. tremuloides* appear dead in our 2010 photographs, suggesting that the trees succumbed to the current drought in the American Southwest (ca. 1996–present; Breshears et al., 2005; Stahle et al., 2009*b*; Williams et al., 2012). Instrumental data and proxy-based drought-reconstructions indicate that this period is among the most severe (i.e., dry and persistent) droughts on record in the Southwest (Cook et al., 2007; Stahle et al., 2007; Touchan et al., 2011).

In addition to the potential effects of variability in precipitation at our rephotography locations, human activities and management policies (e.g., logging, grazing by livestock, and suppression of fire) could have contributed to the vegetative changes we observed (Mangum, 1990; Fire Management Plan of the United States Department of the Interior National Park Service, http://www.nps.gov/archive/elma/JOINTFMP2.htm). A gradual increase in grasses and other groundcover is visible in the foreground of the 1981 and 2010 photographs. The noticeable expansion of surface

TABLE 1—Composition of species within our sampled plot on the interior of the Bandera Lava Flow (34°57′26.9″N, 108°6′24.2″W), 0.71 km southeast of the sites of rephotography near Big Tubes, New Mexico. All stems ≥10 cm in D_{GL} (diameter of tree at ground level).

Species	Year		
	1948	1981	2009
Pinus ponderosa	27	29	29
Pseudotsuga menziesii	7	13	13
Juniperus scopulorum	32[a]	32[a]	32
Pinus edulis	5	6	6
Total	71	80	80

[a] One specimen (34 cm in D_{GL}) not cored due to rot. Based on characteristics of abundant old growth, the tree recruited to ≥10 cm in D_{GL} prior to 1948.

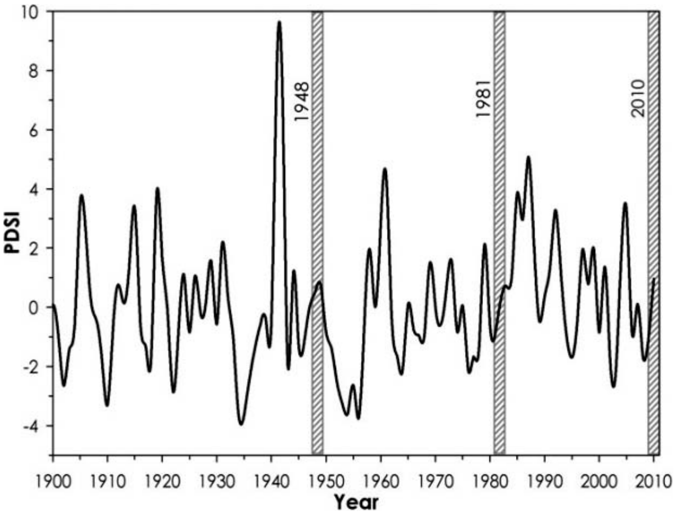

FIG. 4—Graph of mean annual Palmer Drought Severity Index (PDSI; Palmer, 1965) for northwestern New Mexico (1900–2010). Values >0 represent periods of above-average availability of moisture, while values <0 represent periods of below-average availability of moisture. Vertical lines indicate the timing of the photographic sequences analyzed.

vegetation that occurred before the 2010 photographs is consistent with the decline of industrial livestock-grazing during the twentieth century at what is today El Malpais NM. Livestock-grazing ceased across much of the area after the establishment of El Malpais NM in 1987 (Mangum, 1990), which may partially explain the increase in groundcover on the substrate surrounding the Bandera Lava Flow. Recent vegetative dynamics at the edge of the Bandera Lava Flow also might be associated with anthropogenic disruptions to the local fire-regime during the second half of the twentieth century (Grissino-Mayer and Swetnam, 1997; Lewis, 2003; Rother, 2010). The 1948 and 1981 photographs taken by A. A. Lindsey potentially show regeneration (e.g., recovering groundcover off the lava and the recent establishment of *P. tremuloides* at the lava edge) after low-severity surface fires that occurred before the implementation of fire-exclusion management practices. The contiguous groundcover, lack of regeneration of *P. tremuloides*, and the persistence of fuels (e.g., logs) and young conifers visible in the 2010 photographs is consistent with the diminished role of fire at the photographed sites during recent decades.

The stability we observed within the interior woodland plot complements previous studies that showed the longevity of conifers living on the lava flows at El Malpais NM (Grissino-Mayer, 1996, 1997; Grissino-Mayer et al., 1997). The presence of only one lightning-scarred tree, surrounded by living trees, suggests that fire does not spread easily across the broken surface of the interior Bandera Lava Flow. In addition, the inaccessibility and ruggedness of this interior woodland make it unlikely that the location was ever logged, grazed, or inhabited by European Americans. The scarce vegetative changes we observed at the interior site may be associated with minimal anthropogenic activity prior to and during the period of analysis. The persistence of conifers at the site is consistent with the drought-tolerant characteristics of the species (Burns and Honkala, 1990). Several small stems of *P. tremuloides* growing within the plot indicate sufficient availability of moisture on the lava interior, despite the current drought in the Southwest. The survival of *P. tremuloides* at the interior site is in contrast to the contemporaneous decline of the species visible in the rephotography sequences recorded at the lava edge. Persistence of *P. tremuloides* at the interior site during dry periods supports earlier studies (Shields and Crispin, 1956; Grissino-Mayer, 1995) that demonstrated the ability of porous, permeable basalt features to store water during periods of decreased rainfall.

Although the landscape at El Malpais NM is distinct, the disparity between the success of *P. tremuloides* on the lava interior compared to the lava edge is relevant to ongoing discussions about population trends in the species. Romme et al. (2001) noted that *P. tremuloides* is widely distributed and the environmental response of the species varies spatially. However, the decrease of *P. tremuloides* at the lava edge in the 2010 photographs is consistent with the view that the species is vulnerable to sudden decline of aspen across western North America (Rehfeldt et al., 2004). Our findings are particularly complementary to research that suggests the influence of drought and altered-disturbance-regimes on the current decline of *P. tremuloides* (Kay, 1997; Frey et al., 2004; Rehfeldt et al., 2009). Minimal vegetative changes, including the presence of healthy specimens of *P. tremuloides*, at our interior plot might indicate the species is less susceptible to mortality at locations that provide access to stored precipitation during prolonged dry periods. In addition, we observed greater decline in *P. tremuloides* at the lava edge where the frequency, intensity, and agents of ecological disturbance are more dynamic than on the lava interior.

Historical photographs are valuable archives of fine-scale environmental dynamics. Photographs taken by A. A. Lindsey of the mixed-conifer woodlands at El Malpais NM are important tools for investigating vegetative changes across the land-use and ecological gradients of this unique landscape. The photographs provide a visual record of past conditions that can be used to complement forest-inventory analysis, dendrochronology, Geographic Information Systems, and other methods used for ecological monitoring. Although the photographs used in this study do not represent all locations at El Malpais NM, our results agreed with previous studies that suggested the interior of the lava flow insulates against drought, fire, and anthropogenic activities that alter structure and composition of stands (Grissino-Mayer et al., 1997; Grissino-Mayer and Swetnam, 1997; Lewis, 2003).

The rephotography sequences produced by this study provide a record of fine-scale vegetative dynamics at one general location within El Malpais NM. However, our findings are relevant to the broader discussion about the demography of *P. tremuloides* and associated conifers in the Southwest (Kay, 1997; Elliott and Baker, 2004; Kulakowski et al., 2004; Rehfeldt et al., 2009). The dynamics we observed at our rephotography sites might at least indicate vegetative changes at additional locations along the extensive boundary between the Bandera Lava Flow and surrounding substrate. Our findings also show that the old-growth woodlands on the interior of the Bandera Lava Flow may have experienced minimal mortality during drought events that occurred during 1948–2010. The apparent resistance of interior trees to periods of moisture-stress, combined with their insular locations, suggests that the mixed-conifer woodlands of El Malpais NM could persist on the porous, permeable, and relatively inaccessible lava flows despite a potential increase in regional aridity during future decades. The continued use of rephotography, complemented by additional inventories of vegetation and tree-ring analyses, could help clarify contemporary relationships among drought, human activity, and vegetative dynamics on the lava flows of New Mexico and throughout the American Southwest.

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