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Multi-sensor drone survey of ancestral agricultural landscapes at Picuris Pueblo, New Mexico

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ABSTRACT

Although aircraft-acquired lidar has proven to be a transformative technology for archaeology in forested regions around the world, drone-acquired lidar systems that could potentially offer higher-resolution imagery at much lower cost remain difficult to deploy in field settings, while the data they produce are prone to large errors and are challenging to process. This paper presents results of a study that employs a new ultra-compact drone-based lidar system, alongside aerial thermal and visible light imaging, to document ancient agricultural landscapes at Picuris Pueblo, New Mexico. We discuss the advantages of this new instrumentation, various approaches to field data collection, and as well as our novel data processing and filtering methods, which collectively offer key methodological advances for archaeological investigations using drone-based lidar. Results reveal extensive remains of a vast system of terraces and stone-built field systems, preserved below the modern piñon-juniper-ponderosa forests of the Picuris Reservation and surrounding areas. These findings offer new perspectives on the scale and intensity of past agricultural activities in this highland region of the American Southwest, while demonstrating the power of combining multiple drone-based remote sensing datasets with detailed surface surveys to aid in the discovery, mapping, and interpretation of archaeological landscapes in forested regions.

1. Introduction

Analysis of durable remains of ancient agricultural field systems offers perhaps the most direct means to reconstruct the nature, intensity, and chronology of past land use practices. Archaeological investigations of these features can reveal issues ranging from the complex manner in which agricultural modifications to the landscape impacted local environments, to the variable sustainability of past subsistence strategies under dynamic climate conditions, to diachronic changes in settlement composition associated with population growth, political economies, or ideologies of land and labor (e.g.,Miller and Gleason, 1994; McLeester and Casana, Forthcoming). ; Ancient land use data are also an essential component in modeling global-scale land use and climate patterns (e.g., Ellis et al., 2021; Stephens et al., 2019; Morrison et al., 2021), and deeply inform the broader, trans-disciplinary conversation regarding the onset and characterization of the Anthropocene (e.g., Bauer and Ellis 2018). While relict field systems offer historical insights into a wide range of research questions, it is often difficult to document these frequently subtle features, which are easily lost to anthropogenic or geomorphic forces (Casana 2021). Forested regions of the world present a particularly challenging environment for discovery and mapping of ancient agricultural features because tree canopy obscures the ground from most forms of aerial or satellite-based imaging, while surface evidence can be subsequently buried by thick deposits of decomposing organic matter, depending on the local depositional regime. For these reasons, aerial lidar has become an indispensable tool in archaeological investigations of forested regions (Opitz and Cowley 2014), offering researchers the ability to map otherwise unknown agricultural

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landscapes below tree canopy in regions ranging from central America (Chase et al., 2011; 2016; Macrae and Iannone 2016; Stoner 2017), to Southeast Asia (Evans et al., 2013; Klassen and Evans, 2020) ; , to Mediterranean Europe (Bernardini and Vinci 2020).

Despite the popularity and proven power of aerial lidar for archaeological research, its use in many regions of the world has been limited due to the high costs of collecting conventional imagery from piloted aircraft and the low resolution of publicly available datasets (Opitz and Herrmann 2018). The last few years have seen the development of drone-deployed lidar systems, offering archaeologists the opportunity to collect lidar data anywhere in the world, at optimal times in a seasonal cycle, and at whatever spatial resolution is needed (Casana et al., 2021; VanValkenburgh et al., 2020). However, most low-cost, compact lidar sensors remain difficult to deploy in field settings, while processing the resulting data to successfully reveal archaeological features is extremely challenging (Štular and Lozić 2020). The recent development of a new ultra-lightweight, low-cost lidar system (the L1) by drone industry leader DJI offers opportunities to streamline data collection and processing, but the sensor remains largely untested in archaeological contexts and there is little published information on best practices for processing data (Diara and Roggero 2022; Štroner et al., 2021). This paper presents results of a pilot research project that employs the new DJI L1 sensor, paired with thermal and visible light imaging, to successfully document pre-colonial and early colonial agricultural landscapes at Picuris Pueblo, New Mexico (Fig. 1). Results reveal extensive remains of a vast system of terraces and stone-built field systems, preserved below the modern piñon-juniper-ponderosa forests of the Picuris Reservation and surrounding areas. We detail our approach to data collection using the DJI L1 lidar sensor, as well as offering a guide to filtering data that preserves subtle archaeological features hidden from view by modern tree canopy. Our results offer new perspectives on the scale and intensity of past agricultural activities in this highland region of the American Southwest, while demonstrating the power of combining multiple remote sensing datasets with detailed surface surveys to aid in the discovery, mapping, and interpretation of agricultural landscapes.

1.1. Collaborative archaeological and indigenous understandings of the study area

Picuris Pueblo is a Native American community located in northeastern New Mexico, with a long history of occupation (Fig. 1). Investigations of archaeological deposits, some of which exceed 7 m in depth, demonstrate that Picuris people occupied this village location continually since the 10th century, making Picuris one of the longest continually occupied settlements in the continental United States. In 1591, Castaño de Sosa offered the earliest colonial commentary on the community, describing Picuris as a walled settlement with four or more large adobe building complexes, some of which allegedly reached heights of “seven to nine stories” and housed two thousand or more people (Castaño de Sosa et al., 1965; Schroeder, 1976). At the time, Picuris was also home to an indeterminate number of mobile bands—likely Apache—camped a short distance from the pueblo in what de Sosa referred to as a settlement of “huts.” The size and preparedness for defense by the Picuris populace prompted de Sosa to retreat south to Santa Fe out of concern for his group’s safety. Only later, in the early 17th century, was a mission church built at Picuris, with the first clergy describing more than a thousand converts to Christianity.

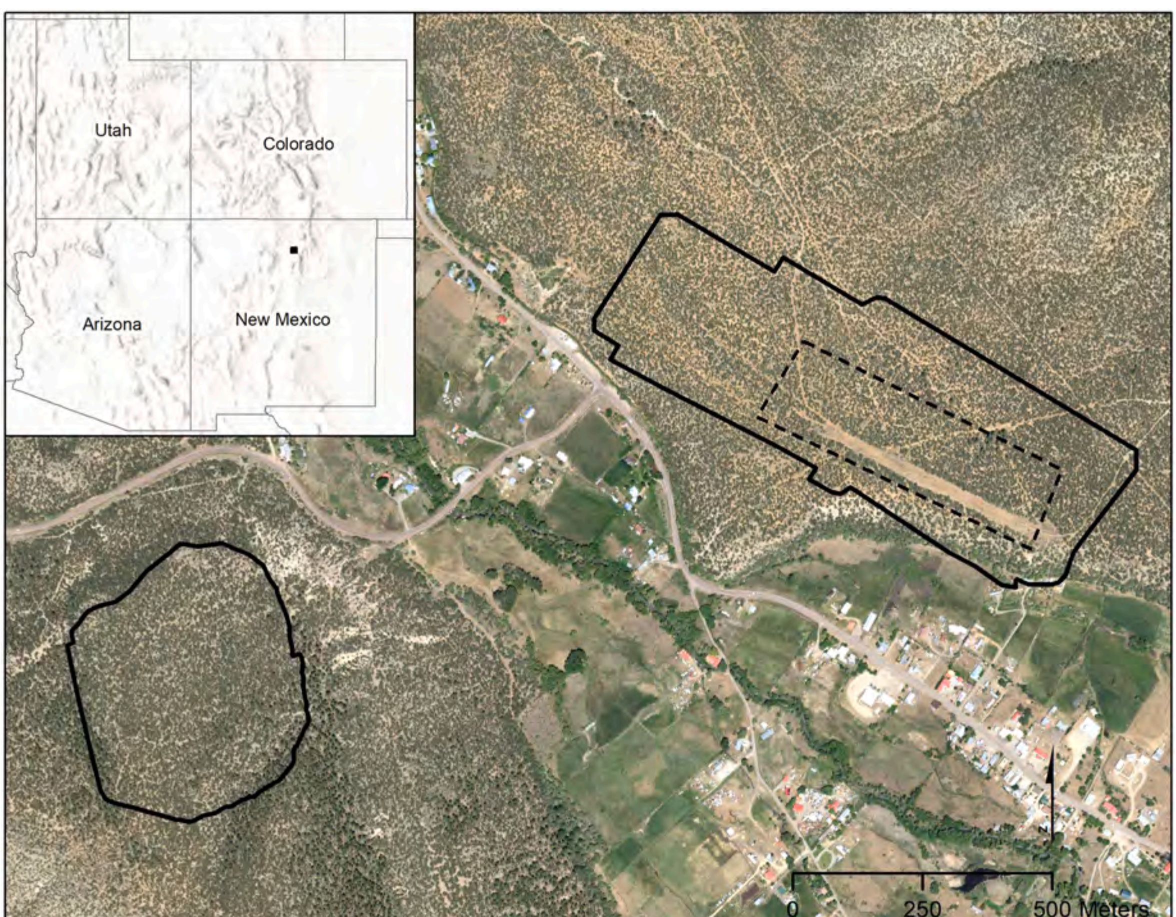

Fig. 1. Locator map showing Picuris Pueblo and the areas of aerial, drone-based lidar (solid line) and thermography (dashed line) undertaken as part of this study.

Though many early Spanish accounts may have inflated Indigenous population sizes in order to request more clergy, military support, and related provisioning from the provincial capital in Mexico City, archaeological excavations conducted by Herbert Dick and others in the 1960s supports de Sosa's description of Picuris as one of the largest Pueblo communities in the Northern Rio Grande (Adler and Dick, 1999; Dick et al., 1999; Dick, 1968) ; . These excavations exposed the foundations of several massive adobe structures, supporting de Sosa's observations from over 350 years earlier. Moreover, recent analysis of the nearly 800,000 pottery fragments recovered during the 1960s excavations suggest that the Pueblo town de Sosa described in the 16th century was likely *smaller* than the 15th century settlement at Picuris.

Following the Pueblo Revolt of 1680–1692, Picuris experienced a precipitous demographic and political decline due to a combination of factors including waves of European-derived diseases, ongoing colonial predation, and the departure of Picuris people from their pueblo as repeated acts of anti-colonial refusal (Kulisheck, 2003; Palkovich, 1985; Reff, 1991) ; . The latter led many—perhaps even most—Picuris people to leave the Rio Grande valley for the Great Plains, joining their long-time Athapaskan allies and escaping life under Spanish rule (Fowles and Eiselt 2023). By the early 18th century, Picuris' population hovered between 150 and 350 people, where it would remain for the next three centuries. Today, Picuris is the smallest of the nineteen Rio Grande Pueblos, with approximately 300 enrolled tribal members.

Results presented herein were undertaken as part of the larger Picuris Collaborative Archaeology Project (PCAP). Since 2017, three authors of this article (Adler, Fowles, Montgomery) and their tribal liaison (Mermejo) have conducted archaeological fieldwork on Picuris reservation lands in collaboration with the tribal community (Fowles et al., 2023), in order to document Picuris' role as an exchange center in the Plains-Pueblo Regional Interaction System (Spielmann 1991). The emergence of Picuris as a regional exchange depot was driven by an unprecedented expansion of bison hunting on the Southern Plains along with the growth and diversification of agricultural production strategies across the 14th-16th century Pueblo landscape. A primary focus of PCAP research has been to expand scholarly understandings of the Plains-Pueblo Interaction Sphere by refining what is known about the scope of Picuris agricultural practices as well as the nature and extent of Picuris trade networks which entailed the procurement of meats, hides, and other resources from the Southern Plains and their exchange for agricultural goods. Our expectation is that communities such as Picuris and other agrarian villages along the eastern flank of the Rocky Mountains, such as Taos Pueblo and Pecos Pueblo, generated significantly more agrarian goods than would have been needed by the community for sustenance, ceremonial events, and local exchange.

To date, PCAP has documented extensive traces of past settlement and agricultural practices through systematic pedestrian survey, GNSS-based mapping, and test excavations across the Picuris Reservation. A preliminary assessment of this fieldwork indicates that ancestral Picuris people produced one of the most extensively modified agrarian landscapes in the American Southwest. The Picuris agricultural landscape is defined by massive complexes of water control systems, comprised primarily of rock alignments and cobble/gravel mulch fields on the gradual slopes of the mesa-top lands, as well as cut-and-fill terracing on steeper south-facing hillsides surrounding the pueblo. Pollen and phytolith analyses designed to clarify the range of crops are ongoing; there is no question, however, that these labor-intensive constructions were designed to slow the movement of rainfall and snow melt and to retain soil in areas of potential erosion.

The PCAP team has employed undertaken pedestrian mapping using Real-Time Kinematic (RTK) GNSS devices to aid in hand-drawing stone alignments and terrace walls in a study area of approximately 10ha. These efforts have yielded a rich body of evidence for ancestral Picuris land use, but it is a time-consuming, labor-intensive method that can vary significantly in precision and detail depending on the experience and skills of individual surveyors. Moreover, dense forest cover and steep terrain add to the difficulties of pedestrian mapping in portions of the study area. To address these challenges and gather data from a larger portion of the Picuris landscape, the PCAP team worked with the lead author (Casana) and other members of the National Science Foundation-funded Spatial Archaeometry Research Collaborations (SPARC) program (Ferwerda and Hill) to undertake a series of drone-based surveys using aerial lidar, visible light, and thermal infrared imaging.

2. Methodology

Drone surveys undertaken as part of this project target two areas known to have extensive traces of past agricultural features. The first drone survey focused on a forested plateau 2.2 km southeast of the historic pueblo, in an area surrounding an early 20th century airstrip where the PCAP team had completed detailed surface mapping of agricultural features and associated artifacts. The plateau is replete with remains of hundreds of linear stone features related to water control and soil retention and dating primarily to the 14th-17th centuries (Fig. 2). Constructed of rounded cobbles, the features measure up to 1.5 m in width and often extend for more than 100 m through the forest. However, these features exhibit very little topographic expression, usually measuring only 5–20 cm above the modern ground surface. Linear stone features are built over an earlier Valdez Phase (900–1200 CE) occupation, visible today as a dense 4-km-long distribution of pottery punctuated by occasional pit house depressions and concentrations of burned daub. Extensive agricultural reworking of the landscape during the 14th and later centuries has presumably obscured most traces of the Valdez Phase architecture that had once stood at the site.

Our second survey area targets the east-facing slope of a high plateau to the southwest, on the opposite side of the Rio Pueblo valley (Fig. 1). In this area, hereafter the South Slope, a reconnaissance visit by PCAP noted the presence of extensive linear stone alignments and terraces, most of which were visible as cut-and-fill features with good topographic variation. While a pedestrian survey of the South Slope has not yet been conducted, it was identified as a strong candidate for lidar mapping due to the well-preserved terraforming and lack of overlying landscape modifications.

Drone surveys were conducted using a DJI Matrice 300 drone, the current flagship "enterprise grade" aerial platform offered by consumer drone industry leader DJI (Fig. 3A). The system offers the ability to deploy a wide range of different sensors that can be configured to attach to the M300's "skyport," a vibration dampened gimbal mount. The M300 is RTK GNNS compatible, such that imagery can be collected with a high degree of precision without need for many ground control points, as long as the drone stays in communication with an RTK base station. In our surveys, we used the custom built DJI RTK-2 base station, although other lower-cost base stations can also be used in its place. Individual surveys were planned using the DJI Pilot 2 app, which, while lacking some of the flexibility provided by other third-party mission planners, is nonetheless capable of basic terrain following and offers a robust and field-ready integration with DJI drones and sensors. Researchers considering a platform like the M300 or the newer M350 should be cautioned that its batteries are too large to transport on commercial aircraft, and thus must be shipped via surface freight ahead of field projects, creating a logistical hurdle in some instances. Drone surveys in upland areas around Picuris Pueblo are challenging owing to the dense forest and steep terrain, often restricting potential launch sites to a few outcrops and clearings (Fig. 3B).

2.1. Lidar

Lidar surveys were executed using the DJI L1 lidar sensor, a compact, lightweight system with impressive performance considering its size and cost. The system reports 240,000 points/second with three returns per pulse, an effective range of up to 450 m, and an accuracy of 5–10 cm. In order to optimize ground coverage and point density, we conducted

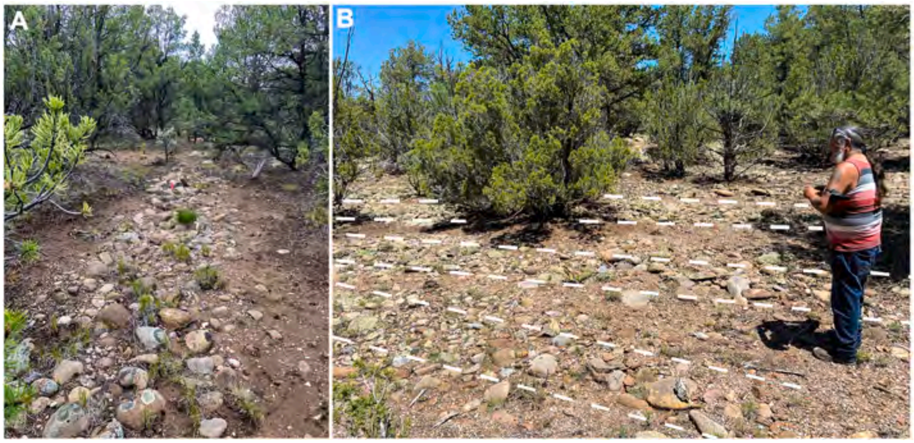

Fig. 2. Photographs of (A) a long rock alignment and (B) a series of low, stone terrace walls at Picuris Pueblo (image credits: Michael Adler).

Fig. 3. Photo of DJI M300 drone with L1 sensors (left) and launch site on the South Slope (right).

lidar surveys at 50 m AGL flying at 4 m/s. In order to improve tree canopy penetration, we planned sufficient side overlap to ensure that all areas of the ground were mapped from at least two and possibly three positions (55% overlap at the less vegetated airstrip; 70% overlap at the more densely vegetated South Slope site). These data collection settings result in high point densities (on average: 1751 points/m2 at South Slope and 937 points/m2 at Airstrip) that increase the likelihood of canopy penetration and ensure sufficient coverage for extracting features of interest.

The DJI L1 sensor outputs data in a proprietary format that requires DJI Terra, the software platform developed by the company for photogrammetry and lidar processing. While licenses for Terra can be purchased to unlock additional functionality, the conversion to LAS file format can be completed with a free version of the software. After converting the raw data to LAS format in DJI Terra, we used LAStools (version 220,107) to process the point cloud (Lastools, 2022). LAStools is comprised of many different tools that allow users to examine, filter, and edit lidar data using either the command line or a GUI. We selected this software for processing and filtering lidar point clouds because it provided the greatest flexibility and most robust filtering at a relatively affordable price (see Supplementary Document).

As a first step in data processing, the point cloud dataset was examined using *lasinfo* in order to determine the density of points, which informs the tiling parameters in the next step. Then, the large point cloud dataset was broken into smaller tiles using *lastile*, with a maximum size of 15 million points per tile to avoid insufficient memory errors when running other tools. Once the tiles were generated, we used *lasground* to classify points as either ground or non-ground. A sample tile was chosen to identify the optimal settings for filtering the data, which is an iterative process as the best settings vary based on terrain and ground cover in the area. While classifying bare earth from a lidar point cloud is relatively straightforward, removing vegetation while keeping sometimes subtle archaeological features such as terraces or building foundations requires much more careful processing to avoid removing them from the point cloud (Fig. 4). This less aggressive approach to filtering and classification preserves many small archaeological features, but also produces a noisier bare earth model that may include many small shrubs, stumps, and rocks. After applying the optimal ground classification parameters to all tiles in the dataset, we then used *lasmerge* to combine the tiles into a single file containing only the ground points. Additional details of our processing protocols are provided in a supplementary document.

While previous drone-deployed lidar sensors required strip alignment to remove significant errors between adjacent survey transects (Casana et al., 2021; Hill et al., forthcoming), the DJI L1 has proven to be much less noisy and much more precise in the alignment, largely due to the RTK capability of the M300. Our data nonetheless includes some

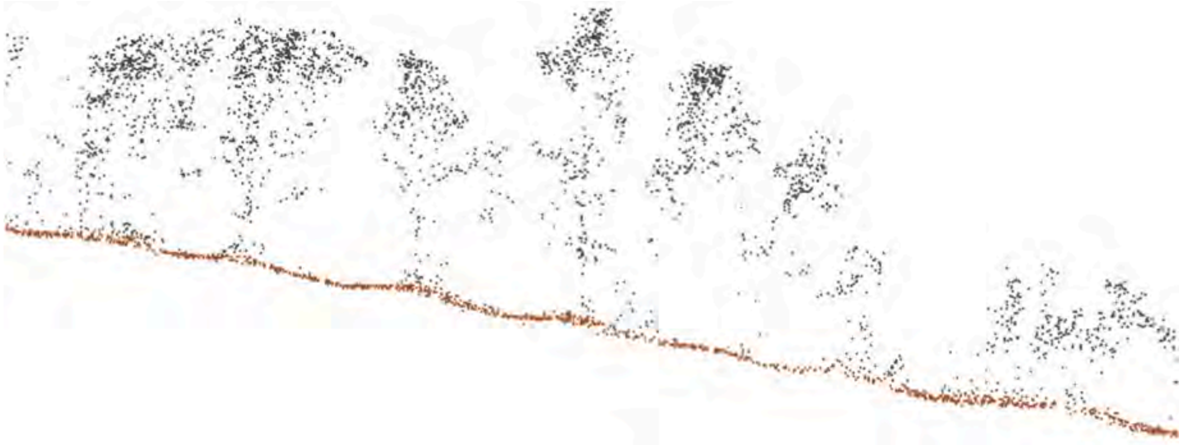

Fig. 4. Cross-section of a lidar point cloud collected at Picuris Pueblo, classified to show "ground" points (brown) versus non-ground (black).

misalignment between transects, visible as lines through the bare earth model. While there are software solutions for aligning strips more precisely, the most effective tools (e.g., BayesMap Solutions) require a significant investment. Although the slight transect misalignment in the data are unsightly, they do not interfere with the interpretation of the data.

Finally, a point cloud containing only the ground-classified points was imported into SAGAGIS and interpolated to create a DTM and hillshade. Care must be taken to ensure an appropriate cell size is chosen that preserves maximum detail in the data while also avoiding holes in the interpolated surface. Once a DTM was created, a hillshade was rendered to reveal topography and features of interest by varying the sun azimuth based on the orientation of features on the ground. In areas with significant elevation change, such as on the South Slope, a terrain-flattened hillshade proved useful for highlighting detailed topography such as terraces. A low pass filter with a 10 m radius was applied to the DTM and then subtracted from the original DTM to remove broad variation in topography (e.g., the mountain slope) and to produce a surface containing only smaller variations in topography.

2.2. *Thermal imaging*

Thermal surveys were executed using the DJI XT2 radiometric thermal camera, essentially a version of FLIR Vue Pro R that is integrated with a 20mp color camera and mounted on a gimbal for easy integration with the Matrice drone line. The radiometric camera collects 14-bit thermal images and offers the ability to adjust a wide range of collection parameters including atmospheric temperature and surface emissivity. Archaeological thermal surveys must be conducted at night, but prior to any dew formation which can mask subtle subsurface thermal anomalies (Casana et al., 2017). We were able to conduct only one thermal survey at Picuris Pueblo beginning at 9:30pm, following an afternoon thunderstorm, a common occurrence during the summer monsoon season. During the survey, the relatively high humidity and a rapid drop in temperature (>5 °C) caused condensation on the camera lens, which created some issues in the absolute values of the thermal images.

Thermal imagery was processed in AgiSoft Metashape Pro. First, the raw values were converted to absolute temperature values by multiplying by a scale factor of 0.4 to convert to Kelvin and then subtracting 273.15 to convert to degrees Celsius (B1*0.4–273.15). Then an orthomosaic was created using the standard structure from motion (SfM) tools in Metashape. As the thermal images are relatively low resolution, this process benefits from having at least one ground control point and frequently requires additional check points to link the images.

2.3. *Visible light mapping*

In addition to lidar and thermal imagery, we also collected conventional color imagery of the survey areas to aid in interpretation of results and to provide a high-resolution orthoimage base map. Imagery was collected using the 20mp camera that is integrated with the L1 lidar sensor, at 60 m AGL with 75% overlap in adjacent transects, producing imagery of 1.64 cm/2 resolution. Images were processed using standard protocols in AgiSoft Metashape and exported as GeoTiffs to QGIS for analysis.

3. Results

We successfully surveyed a total of 55 ha across the two study areas at Picuris Pueblo using both lidar and visible light imagery and collected thermal imagery over a smaller 10 ha area on the airstrip plateau. Drone-acquired lidar proved to be a highly effective tool for documenting many of the stone-built linear features in the survey area, providing a new perspective on the enormous scale of these features. Although lidar may not detect some of the more subtle agricultural features recorded by pedestrian survey, lidar nonetheless proves to be a powerful means of quickly establishing broad patterns over large portions of the landscape, thereby providing important context for interpreting results of more intensive pedestrian survey.

Perhaps the most impressive results from our lidar survey come from the South Slope, an area that is difficult to access and has few viable launch points for a drone survey (Fig. 5). The bare-earth lidar model in this area reveals an extraordinary system of ancient agricultural terraces on the east-facing slope of the mountain (Fig. 6). As is the case elsewhere on the reservation, tribal members were aware of the agricultural features on the South Slope, and pedestrian reconnaissance by the PCAP team confirmed the presence of extensive terracing. The lidar survey, however, enables us to successfully map and visualize these features, showing that they extend over more than 500 m of terrain, particularly on the steeper area of the slope. Terraces are 2.5–3.5 m in width and generally measure 30–50 cm above the modern ground level, though there would have been somewhat greater topographic variation when the field system was in use (Fig. 7). A 3D rendering of the terraced hillside illustrates how the linear ridges follow the natural topography of the hillside, curving around protruding rock formations and being interrupted by deeper gullies (Fig. 6). As the terrain at the top of the mountain becomes less sloped, terraces gradually disappear from view, although it is possible that rock alignments may continue in this area but have too little topographic relief to be resolved in the lidar data. Terraces also fade out on the lower portions of the slope, possibly because they have been buried by eroded talus materials. Confirming the

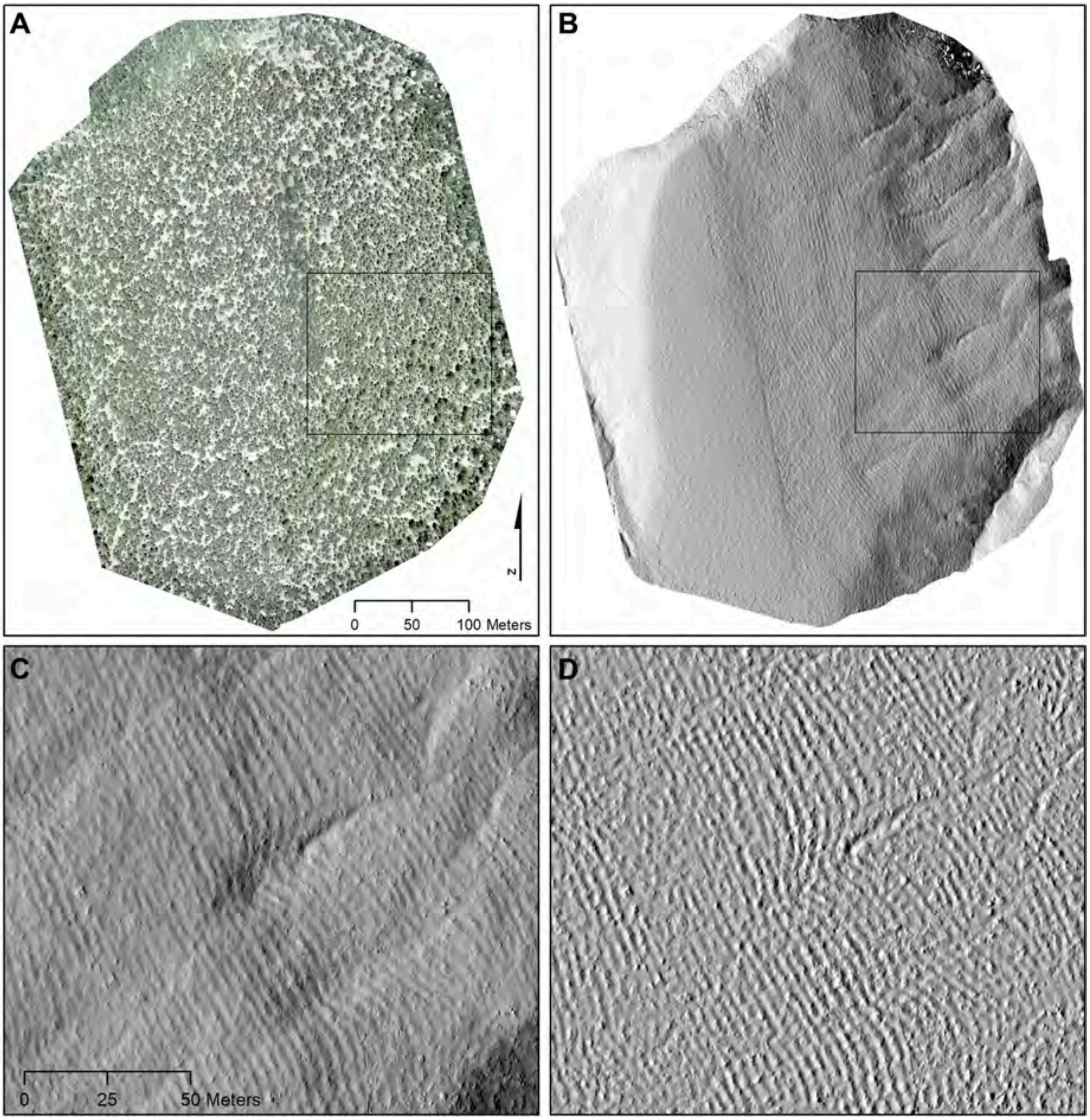

Fig. 5. South Slope A) color ortho image, B) lidar-derived, bare earth hillshade, C) inset showing close-up of lidar-derived hillshade D) inset area illustrated as a terrain-flattened hillshade.

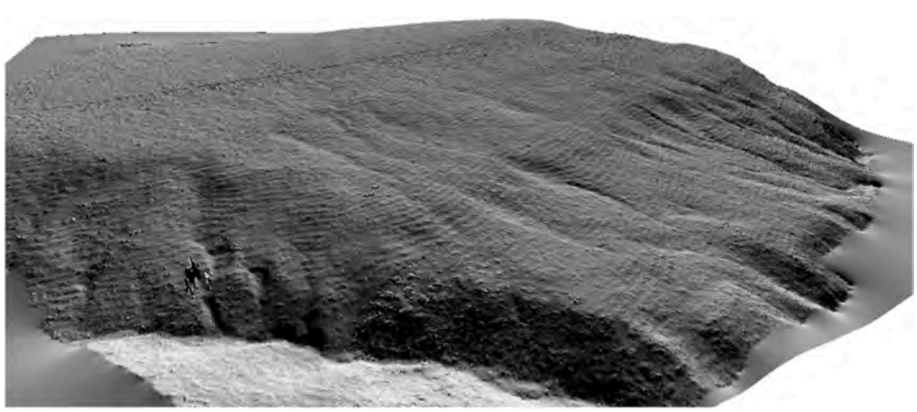

Fig. 6. 3D View of South Slope with a lidar hillshade draped over the lidar-derived bare-earth digital elevation model (see Fig. 5 for scale).

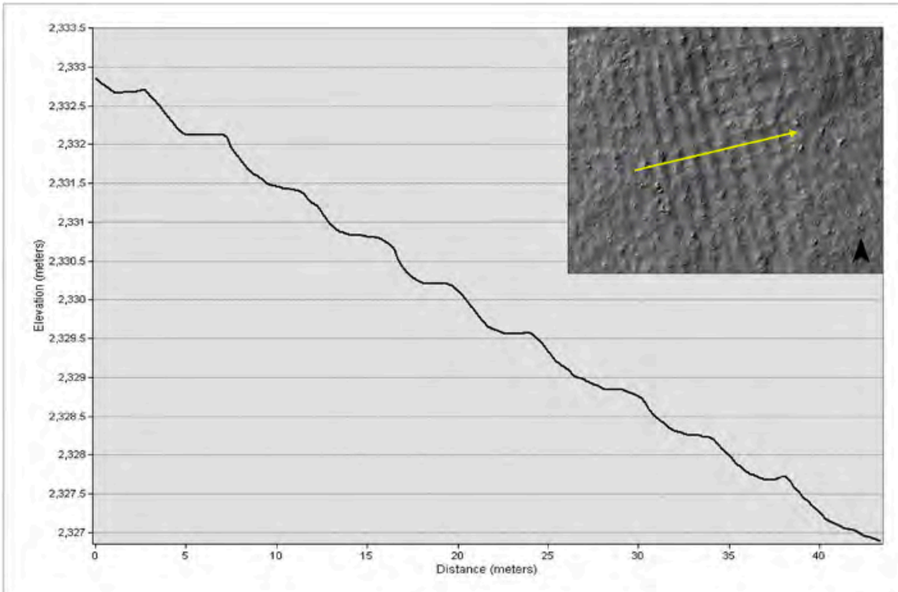

Fig. 7. Cross-section perspective of one area on the South Slope, showing terraces as they appear in the digital elevation model.

presence or absence of agricultural features in areas of less topographic variability await more detailed pedestrian survey. Nonetheless, in one section of the slope, nearly 100 individual preserved terraces are already visible in the lidar data.

Although they are less well preserved, there are also traces of terraces on the west side of the mountain, extending approximately 200 m in length. Faint linear features can also be resolved in some areas on the top of the plateau, suggesting that prior to 17th century, the entirety of this mountain was brought under active cultivation, and was therefore most likely completely deforested. Given the lack of soil development on plateaus in the region and the relatively high visibility of precolonial sites, pedestrian survey can add detail to portions of the lidar-based map that remain unclear.

In contrast to the South Slope, lidar survey around the airstrip area on the north side of the Rio Pueblo does not reveal most known terraces or agricultural fields, primarily because much of this area is a flat plateau with linear stone features that have only very slight topographic relief. However, in areas of somewhat steeper slope on the southwest side of the airstrip survey area, the terraces are again visible in much the same pattern as can be traced on the plateau survey area to the south (Fig. 8). Meticulous mapping of stone alignments using RTK GNSS devices shows that features visible in lidar data correspond well to the stone features that are visible on the ground, although pedestrian survey reveals much greater detail. In this manner, the lidar data is a powerful, complementary method that can be used to document archaeological features over large, remote areas. These landscape-level patterns can help inform survey design while providing an important context through which to interpret the results of intensive pedestrian survey.

In most of the flat areas of the airstrip terrace, linear stone features cannot be resolved directly in lidar data, as they are simply too subtle to distinguish from shrubs, rocks, and other ground cover when filtering the raw lidar point cloud. However, in these areas thermal imagery provides an alternative means for mapping field alignments. In many parts of the survey area where tree canopy is somewhat less dense and ground visibility is higher, linear stone features can be traced in the thermal imagery. Archaeological stone alignments appear as high value (i.e., warmer) features, primarily because the stone used in their construction absorbs, retains, and emits more heat than the surrounding

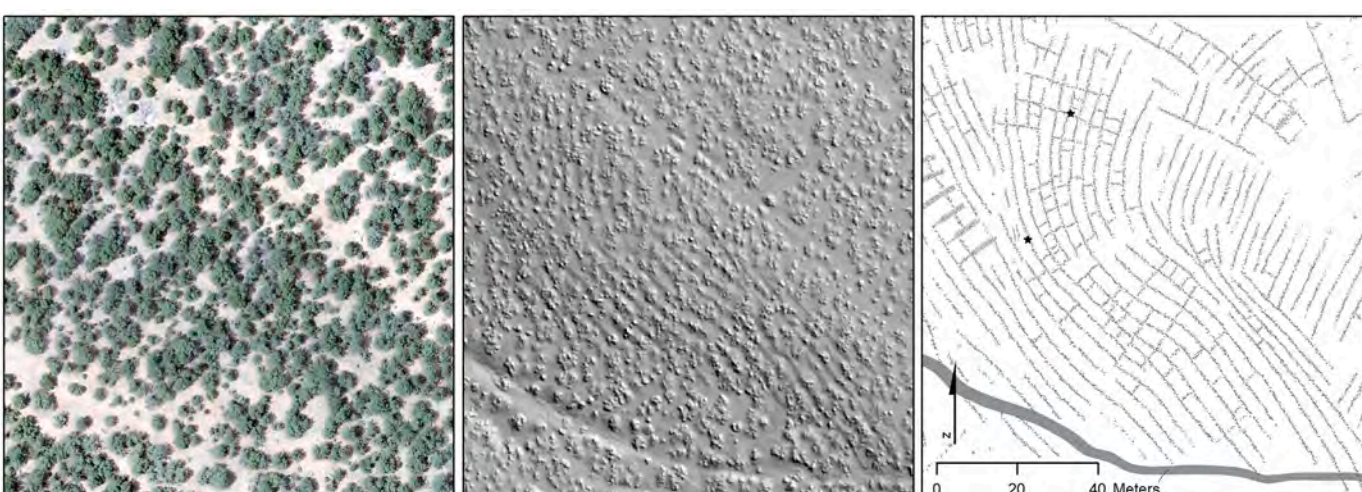

Fig. 8. An area near the airstrip at Picuris Pueblo showing a color ortho image (left), a lidar-derived bare earth hillshade (center), and mapping of terraces by pedestrian survey (right).

soil, and thus appears warmer in nighttime thermal imagery of the site.

For example, in one area of particularly well-preserved features just south of the modern vehicle access road, a series of rectilinear features can be easily mapped over an area of nearly a hectare, with both elongated walls and perpendicular cross walls visible (Fig. 9). Despite the clarity of such features in thermal imagery, they are scarcely detectable—and in many cases not at all visible—as topographic features in lidar data. Similarly, at the eastern edge of the thermal survey, the thermal imagery reveals a dozen or more linear stone features measuring 30–40 m in length that cannot be seen in the lidar data or color imagery (Fig. 10). A brief thunderstorm several hours prior to the thermal survey may have improved the visibility of stone alignments as the rain likely cooled the soil more quickly, heightening the contrast between the stone walls and the surrounding soil.

4. Discussion

Results of the multi-sensor drone survey reported in this study illustrate the importance of utilizing multiple survey methods to document complex archaeological features like the terraces and field systems at Picuris Pueblo. While in this context, pedestrian survey remains the most precise means of mapping the full range of detail, it is time-consuming and yield varying results depending on the particular criteria an archaeologist uses to identify features in the field. In contrast, multi-sensor drone techniques are able to quickly gather data over very large areas, drawing out wider, landscape-level patterns. A collective approach using multiple remote sensing tools in combination with intensive pedestrian survey enables a more comprehensive analysis of large-scale archaeological landscapes. The lidar survey data allows us to document and map field systems and other archaeological features very efficiently, even over very large and/or inaccessible areas, though these data cannot reveal features that lack significant topographic expression. Thermal imaging likewise offers a unique complementary tool, offering the ability to resolve stone alignments and other architectural features with great clarity, but only in cases where vegetation and tree cover is sufficiently sparse for some visibility of the ground. Combining these and other remote sensing tools with pedestrian surveys in sample areas can be used to create a more comprehensive visualization of the scale and dimensions of landscape modification by Indigenous communities like Picuris Pueblo.

One of the most striking facts reinforced by our results is the massive scale of landscape modifications represented by the terracing and other field systems at Picuris Pueblo. Vast areas of the landscape surrounding the occupational core of the Pueblo that today are densely forested were likely instead covered with extensive agricultural fields, supporting crops of maize and other cultigens. Individual terrace walls at Picuris, measuring in excess of 300 m in length, are some of the largest known terraces in the American Southwest (Doolittle 2000), and attest to the truly massive investment of human labor in their construction and maintenance. The sheer number of terraces and field walls documented at Picuris offers unprecedented opportunities to explore the ways in which these features enhanced local agricultural productivity, the potential environmental impacts of both their construction and abandonment, and the social implications of the labor required to build and maintain this vast agricultural project. Although archaeological examples of terraces and other similar stone-built agricultural field walls are commonly encountered in the region, few have been systematically mapped and analyzed due to the challenges in locating and documenting

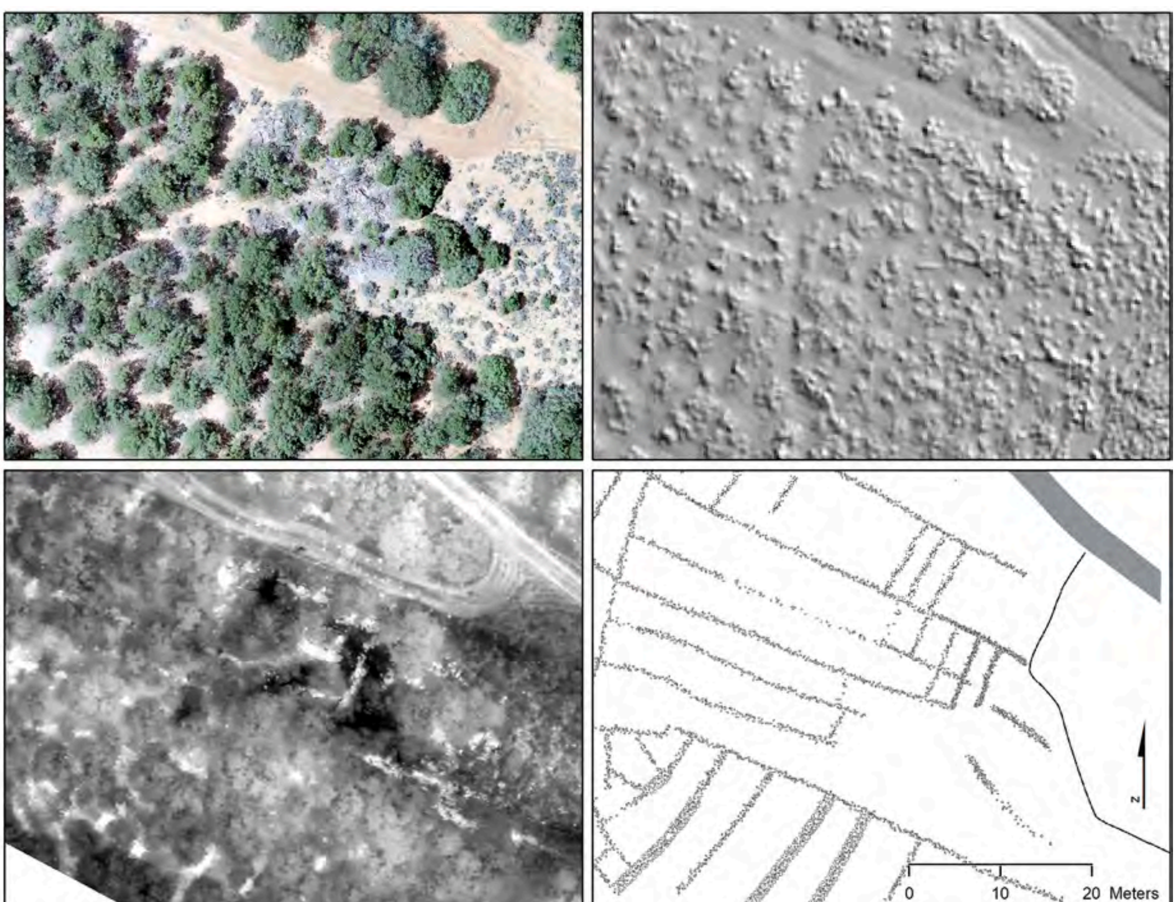

Fig. 9. Airstrip west showing a color orthoimage (upper left), a bare earth lidar hillshade (upper right), thermal imagery where high values represent warmer features (lower left), and field systems mapped through pedestrian survey (lower right).

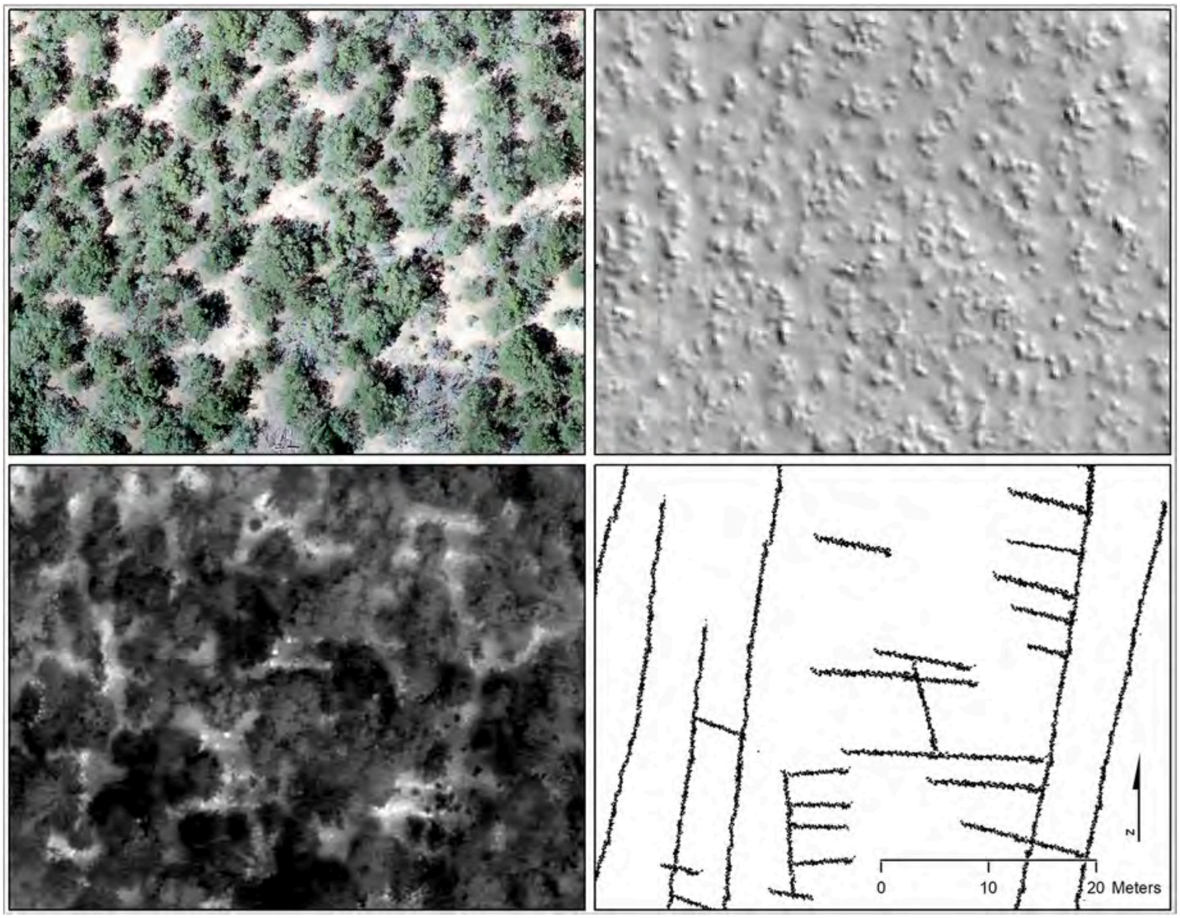

Fig. 10. Airstrip west showing a color orthoimage (upper left), a bare earth lidar hillshade (upper right), thermal imagery where high values represent warmer features (lower left), and field systems mapped through pedestrian survey (lower right).

these landscape features over large areas. Drone-based surveys offer a new perspective on the extent of the ancient agricultural landscape at Picuris Pueblo, serving as a model for future studies in other areas of the Southwest.

Although the scale of the features at Picuris Pueblo is manifest, their function remains a topic of debate and ongoing investigations, in part because there is sparse ethnographic or historical evidence for the use of terracing or other similar water and soil retention approaches to farming among Puebloan communities of the Upper Rio Grande Valley, despite the relative prevalence of archaeological examples of terracing (Doolittle 2000). Archaeological and enthno-historical investigations of agricultural terraces in upland regions around the world, from Mediterranean Europe (e.g., Grove and Rackham 2003; Butzer 2005) to the Peruvian Andes (e.g., Erickson 2000; Langlie 2018), demonstrate many of the benefits of terracing in mountainous regions. Terraces can enhance agricultural productivity by retaining moisture from both rainfall and runoff, inhibiting soil erosion, controlling the flow of surface water, and promoting development of enriched soils on flat areas behind terrace walls. Stone walls and alignments on flat mesa tops that are found at Picuris and other contemporary sites in the region likely served similar functions, helping to trap water from rainfall events and promoting soil development within farmed plots. Some scholars have also argued for the importance of temperature control as a key aspect of these features, as soils that develop on terraces, the moisture retained behind terraces, and the stones used in terrace construction can all serve as heat sinks (e.g., Zhao et al., 2021), a fact that is well illustrated by our thermal imagery. Even a modest amount of heat retention could potentially extend the growing season by critical weeks in a highland environment like Picuris, where late spring thaw and early frost can present challenges to cultivation of maize and other cultigens better suited to warm, humid environments. The precise manner in which the extraordinary agricultural landscape modifications found at Picuris functioned to improve agricultural productivity is the topic of ongoing investigation, but the remote sensing datasets presented here will offer a powerful tool for analyzing their potential impacts on soil moisture, development, and temperature.

5. Conclusions

This paper presents results of multi-sensor, drone-based remote sensing survey of pre-colonial and early colonial agricultural landscapes at Picuris Pueblo, New Mexico, undertaken as part of the ongoing Picuris Collaborative Archaeology Project (PCAP). Although pedestrian survey has established the presence of an extraordinary number of agricultural features preserved across the Picuris region, conventional mapping is time-consuming, labor-intensive, and expensive; it would take decades to generate a representation of the Picuris agricultural system at a landscape scale. At the same time, traditional aerial and satellite imagery are of little assistance due to the dense forest cover and steep, rocky terrain which obscure archaeological features from view. Here, we utilize a new, low-cost, drone-based lidar sensor, the DJI L1, in combination with nighttime thermal and visible light imaging, to map stone-built terraces, linear walls, and other agricultural features over an area of 55ha across two plateaus. Our approaches to data collection offer a guide for other archaeologists seeking to utilize the drone-acquired lidar data in research projects. Similarly, we detail our iterative methods for processing drone-based lidar data, which successfully filter out vegetation while preserving the subtle topographic expression of surface archaeological features, revealing a remarkably well-preserved terraced landscape. Furthermore, in areas where ancient stone walls and fields are too flat to be resolved in lidar data, we show that thermal imaging is a powerful complementary tool, as stone features are visible as heat sinks that can be detected through sparse forest canopy. Our results provide stunning visuals and map data that illustrate the enormous scale of ancestral Picuris agricultural landscapes, contributing to ongoing research investigating cultural and historical contexts of these huge investments in agricultural production, the way in which this unique system of farming functioned in light of a dynamic climate, as well as the environmental impacts of construction and abandonment of fields and terraces in this high-altitude region. More broadly, our methodology demonstrates the potential of rapid, low cost, and noninvasive multi-sensor drone-based remote sensing surveys for discovery, mapping, and interpretation of archaeological features, offering a blueprint for other sites in the Southwest and beyond.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary document providing addition technical details on lidar processing methodology can be found online at https://doi.org/10.1016/j.jas.2023.105837.

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