LAS POSITAS COLLEGE

Las Positas College

Campus Hill Vineyard Topographic and Multispectral Survey:

Unoccupied Aerial Systems (UAS) – Drone Report

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Acknowledgements

The addition of drones to the Las Positas College list of equipment represents the efforts of various individuals on campus who over the course of eighteen months have contributed to making this work possible. This report demonstrates the value of drones, termed in industry as Unoccupied Aerial Systems (UAS), to CTE and other programs on campus. Daniel Cearley would especially like to thank Rifka Several and Vicki Shipman. Rifka provided critical guidance to him after his LPC Foundation grant proposal was rejected, yet her encouragement and advice led him to connect with Vicki. Vicki provided invaluable advice about how UAS training and supervised research could excite and inspire students as a cutting-edge component of CTE. This project would have not been possible without Vicki's advice, determination, and ability to secure funding not only for the equipment, but the monies to allow specialized training for faculty. Most significantly, Mike McQuiston in Administration of Justice led our efforts in attending Drone University trainings and taking part in the 2019 Santa Rosa Junior College Drone Symposium. These two experiences galvanized the resolve that Las Positas College would benefit from these technologies. In addition, David Everett in Viticulture and Winemaking Technology was equally critical in early planning and subsequent field work. His expertise and collaborative spirit have allowed this report to mature.

UAS are types of remote sensing technologies with the potential for application across seemingly disparate disciplines. Their promise is both exciting and confounding. Colleagues in Anthropology, Administration of Justice, Fire Technology, Photography, and Viticulture enthusiastically participated in cross-disciplinary conversations that made it possible to identify shared objectives and individual program needs. Deans Nan Ho and Stuart McElderry guided our efforts throughout. Key campus actors involved in the everyday activities that drove this project forward include Sean Prather and his team in Public Safety and Steven Gunderson and his staff in Technology Support, especially Michael Furuyama and Fernando Calzada. The broader cross-disciplinary conversations and collaborations motivate and inform this initial application of UAS to an LPC-sponsored project. We regard this report as an example of an interdisciplinary application of UAS that brings together two faculty in the viticulture program and anthropology department. We regard it as a productive departure point for future interdisciplinary applications of UAS with our colleagues in other disciplines and look forward to their feedback as the project progresses.

We would also like to acknowledge the important role that students played in the development of this project. The students in the 2020 Spring ANTR 2L course, Archaeology Field Laboratory, unpacked logged, inspected, installed colored protective skins, and tested each drone: Sonja, Stephanie, Theodore, Rebecca, Gavin, Adam, Timothy, Emily, Hunter, Lewis, Crystal, Sarah, Katrina, Jackson, Esther, Emmanuel, and Laura. Every time the drones are in use, the unique color of each recall our shared excitement and enthusiasm when we first unpacked the equipment. Anna, Gavin, Laura, and Garion especially played a critical role in field testing and support.

Thank you all!

INTRODUCTION

One of our missions at Las Positas College is to create new, unique, and cutting-edge opportunities for students. The recent introduction of drones into our curriculum reflects this spirit of opportunity and opens a wide array of exciting possibilities to a broad range of programs. This report focuses on how drones can be applied to our Viticulture & Winery Technology program, yet it also my provide inspiration for others. At the outset we had limited understanding of how this effort would unfold, yet after training, research, and perseverance we now actively use drones monthly to monitor the Campus Hill Vineyard. The following pages represent a series of lessons learned and will help form aspects of our curriculum in subsequent years. Based on our experience, we can easily visualize the potential drones offer for employment and career advancement. It is our hope that future students will be prepared to quickly access well paid employment and enter the workforce with a new mobile skillset that are in high demand in the emergent drone industry.

Is a drone a drone? We commonly use the term drones, yet this label tends to be shunned by the industry for the more technical phrasing which prefers Unmanned Aerial Vehicle (UAV) or Unmanned Aerial Systems (UAS) to take into account that the drone itself is only a single component of a wider series of parts, one of which is the pilot. The word aerial is often interchangeable with airborne and the use of “Un[man]ned” contains obvious gender biases which has been challenged by many with one alternative suggestion is to use the term “Unoccupied” instead (Joyce 2021). In Australia “unmanned” is discarded in favor of “remote pilot,” which is quite thought provoking since our Federal Aviation Administration (FAA) refers to the person operating the drone as a “remote pilot in command.” In this report we have chosen to use Unoccupied Aerial Systems (UAS) to align ourselves more firmly with advocacy for a gender-neutral adoption.

UAS are increasingly being used to measure crop health and document agricultural land topography as they provide an alternative cost-effective, data-rich, and rapid form of remote sensing. Unlike their predecessors that primarily capture satellite-level imagery of large geographic areas, the more affordable and compact fixed-wing and multi-copter units available today fly at low altitudes and capture high-resolution multispectral images of smaller agricultural areas. This micro remote sensing allows for various agricultural indexes to be created from multispectral data. Rather quickly crop managers can assess plant health and observe biomass change overtime. Moreover, the compilation of data collected at various altitudes generates topographic images useful for assessing general area usage and terrain analysis. Data collection and data analysis are relatively quicker processes when compared to satellite or small aircraft based remote sensing or direct field observation survey that are labor-intensive and slower.

As an emergent method of agricultural crop surveillance, UAS are implemented in varied ways. In the absence of a standard protocol, we reviewed current literature and identified key practices that have the greatest application for crop and agricultural land use management. From our review of the literature, we believe that the application of UAS in the agricultural sector is a growing field (Reynolds 2018). We believe that Las Positas College is uniquely positioned to contribute to the growing literature, knowledge base, and training for this newer application of UAS.

The Las Positas College Viticulture and Winery Technology program farms its own, 4-acre, hillside estate vineyard and is one of the few bonded wineries at a Californian institution of higher education. The Campus Hill Vineyard can be likened to an ideal experimental island. It is a relatively compact location with a diverse suite of characteristics with differences in grape varieties; topographic features; row orientation; trellis technique; and irrigation methods. The vineyard produces a wide range of red and white varietals from nine grape varieties (Figure 1). Its position on a triangular shaped hill provides three distinct slope aspects with differing orientations and is separated in four areas called blocks. The Hilltop Block has vine rows planted east/west, the East Slope Block has vine rows planted east/west, the South Slope Block has vine rows planted north/south, and the Heritage Block is grid orientated. In the Hilltop Block, the East Slope Block, and the South Slope Block, the vines are bi-laterally trained on a modified VSP trellis and spur pruned. According to a more traditional approach, the vines in the Heritage Block are head trained and spur pruned. Unlike the other three blocks which are irrigated, the Heritage Block is dry farmed which is a more sustainable type of farming.

Goals and Objectives

This report documents the first application of UAS on the Las Positas Campus. Our intention is to develop a series of best practices for monitoring and investigating cogent research questions pertaining to the different characteristics of the vineyard. These best practices include ongoing review of relevant scientific literature, developing a series of calculated flights that best consistently collect data, and generating useful research results.

We aim to answer the following methodological questions:

- What images and reports can be produced from the data?
- How can we accurately interpret the data?
- Which images and reports are the most useful for viticulture managers?

Our goal is to become fluent in data acquisition and analysis to the point where we can answer the following research questions:

- What is the overall health of the vineyard?
- Why are certain areas similar to or different from others? What characteristics are most important to measure to evaluate these similarities and differences?

The pre-flight planning and post-processing of the images and resulting data sets is the most important and time-consuming side of the work. To develop best practices, we will track pre-flight planning and evaluate the ratio of flight time to data processing. We have learned thus far that every minute a UAS is flown corresponds to hours of time spent in preparation, set-up, breakdown, storage, data transfer, data processing, data interpretation, and refining skills and troubleshooting the different software programs involved in data collection, data processing, and geospatial analysis. For each flight ranging from five to 20 minutes pre-flight planning and post-flight data processing and initial analysis take several days.

Our detailed accounting of this process will elucidate whether our campus application of UAS to viticulture could be be extended as a technological service to the wider viticulture community in the Tri-Valley area and be developed as a model for a UAS consulting business. The end result may lead to questions about longer term employment and career questions our students may be asking:

- *Can this be a profitable venture for me? Is this a scientific technique that I may develop for higher paying jobs in the agricultural sector, my own small business, and/or remunerated opportunities as an independent contractor?*
- *What are the different skills and analytic abilities that I need to develop in order to understand this emergent field and become an effective practitioner? What other courses or internship opportunities do I need to help me develop these skills?*
- *What aspects of UAS technology are more labor and cost intensive and how do I develop a role for myself and business plan that will yield the most profit?*

Section Summaries

The report is written in a similar manner to the workflow of how UAS is applied in agriculture. It will walk us through major steps in the process: the flight planning, data acquisition, post-processing, data analysis, and a summary of our lessons learned.

We will begin describing the **Survey Area and Flight Planning** the which is the most important part of the process. The flight itself requires understanding the local, state and federal legal parameters and ensures that flight is conducted safely. In the case of Las Positas College and its proximity to the Livermore Airport, the legal context shapes the flight characteristics. As will be explained, being constrained to a certain altitude influenced our flight path and image quality for the better. We tested various flight patterns and ultimately chose one which allowed for excellent image quality with the least time spent in the.

The next section talks about **Data Acquisition** and the different types of data that can be captured with emphasis upon the multi-spectral sensor package that provides the five bands of visible and non-visible light. Although this can be technical, it helps us form interesting research question in future endeavors, for example, the manufactures tended to fly four times the height of our test, resulting in low pixel resolution, in contrast we had excellent results at a lower altitude provoking us to consider, “how low can we fly and still maintain image quality?”

Once we understand what can be collected, we review the **Post-Processing**. During flight the cameras or sensors collect hundreds if not thousands of images. This is the raw data that is gathered and is not very useful until it is post-processed using photogrammetry algorithms. These algorithms search each image to locate common points, which than can be used to calculate relative distance among features in the images. The result is a series of large high resolution singular images, these are actually a finely stitched together mosaic - thousands of images become one. These called raster images with each pixel given a value, the value can indicate elevation, light intensity, or reflectance for each band. Some can be viewed in 2D or 3D and are immediately useful, like the digital surface model which shows every detail of the vineyard, yet others still require further process in different software.

The following section titled **Agricultural Analysis** makes up the bulk of the report and is where the individual bands of light are used in mathematical formulas to create unique agricultural indexes and other outputs that are central to agricultural analysis. It is intended to be comprehensive with a wider range of analysis preformed than what some vintners recommend and includes a subsection on calculating biomass. Each of these outputs use zonal analysis to disaggregate the data, a process which holds the potential for future exciting avenues of research. Most importantly, these sub-sections experiment with how the data is represented using a series of maps and charts. These diagrams would be able to directly inform the vineyard manager and their students about areas of interest. This is where the data analysis can be actively integrated into management practices and course curriculum.

The last two sections summarize the main lessons learned throughout this process. It speaks to some of the major achievements, but also recognizes the limitations of the current work. In a thoughtful and comprehensive manner, we layout some of our recommendations for moving forward and a vision for how UAS may form a significant element to the Viticulture & Winery Technology program.

SAFETY AND SURVEY AREA

The Campus Hill Vineyard is located at the main entrance of Las Positas College, at the south corner of Campus Hill Drive and Campus Hill Loop (Figure 2). The prominent and bucolic vineyard both welcomes visitors and provokes curiosity. To the onlooker at ground level, the vineyard looks like a relatively small hill, yet its triangular shape is revealed in maps and aerial images. It is bounded by the Campus Loop road to the north, the Campus Drive to the east, and a multi-use trail for pedestrians and cyclists to the south. The trail acts as a shortcut from the Campus Drive to the Campus Loop and runs alongside the vineyard's southern border on one side and a line of olive trees that buffers a large condominium complex on the other. With the rise of the vineyard on one side and the olive trees on the other, pedestrians and cyclists travel through a relatively quiet and tranquil area before reaching the bustling part of the campus.

The campus viticulture area presents certain challenges to planning drone flights and the collection of data. UAS are prohibited from flying over people, roads, and pathways and there are additional restrictions due to the vineyard's proximity to the Livermore Municipal Airport, approximately one mile south. Depending upon the wind conditions, the airspace over the LPC campus may include part of the approach and landing routes of flights in and out of the airport. These flight patterns are readily apparent to campus visitors as the airport has active flight schools and an enthusiastic aviation community. This means that the campus and a large part of the Tri-Valley is within FAA controlled airspace. The airspace over Livermore Municipal Airport (LVK) is circular shaped and classified as Class D airspace with a particular set of restrictions ultimately administered by the Federal Aviation Administration (FAA) and are under the control of the airport tower or air traffic Control (ATC) who control or direct air traffic in and out of the area. All flights must be approved in advance through the FAA Low Altitude Authorization and Notification Capability (LAANC) system by using an FAA app approved (B4UFly and AirMap were used in pre-flight authorizations). Most proposed UAS flight plans that comply with altitude restrictions receive an automatic authorization. The limits to where and how high one can fly are available through an FAA website (FAA web based map). Elevation restrictions varies from 0’ (totally prohibited) to 400’, usually in increments of 100’. For instance, at each end of the runway the height is zero, yet the height increases as one moves away from the airport. The farther one is away from the airport, the greater the altitude one can fly a UAS (Figure 3). UAS flights over the campus winery is restricted to below 100’ (Figure 4).

Testing Different Flight Routes

We preprogrammed each of the flights which meant that the UAS were automatically operated except for the landing. In automating most of the operation of the flight, we were able to reduce pilot error and thus maintain consistent flight paths. Automating the flight also freed up the pilot’s attention to better monitor both the UAS and surrounding area. This helped the pilot maintain situational awareness of potential hazards from people or other aircraft from entering the flight area and thus respond accordingly to direct the UAS from flying over any passersby or near unexpected aircraft

We used three different flight survey patterns: a grid, a line, and spiral. We conducted the grid survey with a smaller drone without the multispectral package which provided a preliminary image that allowed us to create the subsequent survey patterns. The line and the spiral pattern were compared to test which would provide the highest quality of data in the most efficient manner. They provided different results and were useful in helping us improve our flight paths.

We closely followed upon the manufacturer’s recommendations (Micasense) as we tested out flight paths and refined them. We focused on the three main factors that influence the quality of the data collected: the elevation, the speed of the UAS, and the overlap among the images. The higher the elevation the more area is covered and the lower the resolution. Faster flights collect fewer images with potentially poorer resolution. Overly slow flight patterns generate an abundance of images with an unnecessary repetition of data. A minimum of seventy-five percent (75%) overlap is recommended by the sensor manufacturer to ensure that the photogrammetry algorithms properly function with a sufficient number of reference points. In three different surveys in June and July, we had the opportunity to troubleshoot problems and ultimately devise flight paths that allowed for adequate overlap among the images.

We conducted our first survey in late June. The line survey pattern is the default pattern used by the flight planning software and is most effective in flat topographic landscapes. The UAS flies in a series of parallel lines in a back-and-forth motion with the UAS moving from one end of the area, rotating 180 degree to perform a U-turn than moving to the limits of the area and repeating another turn. In an uninterrupted manner a series of overlapping back and forth paths are created. We used a constant altitude and speed. The elevation changes of the vineyard compromised some of the sensor coverage (Figure 5). At the lower elevations the sensor had a high number of overlapping images. As the path neared the peak the sensor coverage suffered. This was caused by the sensor being closer to the surface at the peak which narrowed the window for the sensor to capture data.

To address this problem of decreased overlap at the peak with the line survey, we conducted two spiral surveys. A spiral grid survey follows a circular path around a center point. On our first spiral survey, we kept the altitude at a constant. We achieved the same quality of overlap at lower elevations as with the line survey and encountered similar problems with reduced overlap at the peak as illustrated by (Figure 6). We noticed that the decrease in overlap was apparent in how the flight paths looked spaced more widely from one another towards the top of the hill. We could have narrowed the routes to compensate, however after further review of the manufacturer’s recommendations, it indicated that maintaining a constant altitude was more important even if there was consistent overlap. We than devised an “on-contour” flight that is at a constant distance between the UAS and the surface of the hill, we devised a second spiral survey with variable altitude and consistent distance from the surface of the hill.

In this second spiral survey in July, we preprogrammed the flight of the UAS to begin at a low altitude around the base of the hill and travels upward with the rising slopes of the hill and peak to maintain the same distance between the UAS with the surface of the hill throughout the flight. We also simultaneously increased the increased the speed and tightened the transect paths to shorten the duration of the flight without compromising overlap (Figure 7).

We devised flight paths with the manufacturer-provided internal controller software by DJI. We soon encountered the limitations of this software as it did not provide an option for on-contour flight path preprogramming. We had to manually calculate and input variations in altitude to stay on-contour with the second spiral survey. Additionally, we found that we could not customize the settings according to the different cameras and sensors we used in capturing images We searched for more robust and flexible subscription-based and open-source alternatives to pre-loaded software. After two days of searching for alternatives and conducting some tests with the other software, we ultimately concluded that the manufacturer-provided software, with its low learning curve, was adequate for this first report although it was time- and labor-intensive for the manual calculations and data input necessary for on-contour surveys of variable speed and width of flight path. For future projects, we intend to further research software alternatives and recommend that colleagues interested in conducting UAS survey projects search for better preprogramming software as well.

DATA TYPES AND ACQUISITION

The UAS is a DJI Matrice 210 which is a commercial grade UAS that can carry a relatively large load for different types of equipment. It has two mounting points for two different cameras or sensors. The Matrice has camera with a lens quality similar to 35mm. It is manufactured by Zenmuse, model X5S with a Micro 4/3 sensor that has a dynamic range of 12.8 stops. The range of f-stops allows more flexibility in differing lighting scenarios and capturing different active scenes. It is a professional camera capable of stills and video. Alone this camera can produce high resolution orthomosaics, 2D/3D point clouds, and other surface relief products, yet since it only captures a single image in an RBG (Red, Blue, Green) composite, it was not used in the vineyard survey, instead a multi-spectral camera was employed. An orthomosiac image was created using the lower resolution multi-spectral camera (Figure 8) and in future flights a combination of both cameras may be employed.

Multispectral Sensor Data Collection

In contrast to the normal camera arrangement described above, the multispectral sensor is a type of camera, yet instead of capturing a single image in RBG, it takes five simultaneous images from five separate sensors, each capturing a certain wavelength (Figure 9). In comparison to the normal camera, the images are lower quality stills, that are saved to the aircraft in JPG formats. Each are geographically tagged and can be positioned in their approximate location. In the future, we should consider installing ground control points to make more accurate comparisons among subsequent data sets.

The sensor is made by Micasense and it is a RedEdge model simultaneously captures five separate bands of visible and non-visible light (Blue, Green, Red, Red Edge, and Near Infra-Red). When Red, Blue, and Green are layered together it creates the images like any other camera which produce a normal color spectrum. The two additional bands by themselves do not necessarily show useful aspects for agriculture, instead these are used perform additive, subtractive, and divisive calculations to highlight certain reflective properties of the vegetation.

- Blue (475 nm center, 32 nm bandwidth),
- Green (560 nm center, 27 nm bandwidth),
- Red (668 nm center, 14 nm bandwidth),
- Red Edge (717 nm center, 12 nm bandwidth),
- Near-Infrared (NIR) (842 nm center, 57 nm bandwidth)

The images produced exhibit impressive quality, yet the range of this quality is unclear after reviewing the manufactures documents. The camera focal length is fixed at 5.5 × 4.8 mm. This means that there is an optimal height which it can collect images without quality issues. The manufacture does not necessarily have a specific recommended range and uses examples often in the 100+ meter range. Flights over the vineyard were at an altitude of 30m (100’) Above Ground Surface (AGL) creating surprisingly high resolution at ground of 1.869 cm/pixel. At higher altitudes the pixel size increases, for example at 100 m altitude flight has reported as 6.82 cm/pixel (Boiarskii 2019) and at 120m 8 cm/pixel (Micasense 2019). At 30m AGL individual vines can be distinguishable although finer detail is obscured within the central trellis canopy (Figure 10). Lower elevation flights have not been tested, yet at a certain point the resolution will be limited by the sensor focal length to cause distortion. This would be a very easy and useful test to conduct.

POST PROCESSING

Overview

The post-processing of the images occurs in two stages. The first part employs photogrammetry and the second involves remote sensing analyses with GIS software. The images are initially uploaded to one of two photogrammetry programs. We are currently testing two differing software packages, Pix4D, a commercial product that is subscription based and an open-source freeware called Open Drone Mapper.

Each of these are designed to stitch together the images by comparing how each overlap. These programs use photogrammetry algorithms to create a series of 3D data sets. Secondly, once this data is processed it is imported into a geospatial program (GQIS and/or ESRI ArcMap) which allows for more advanced comparative analyses, statistical calculations, and geospatial work. For each of these processes, an open source and a commercial grade program was utilized for comparative and educational purposes. It should be noted that a third suite of programs are commonly used with these files that focus on 3D modeling and terrain mapping.

Data Outputs

There are three main data sets created by the photogrammetry programs: a 3D mesh and 3D point cloud, orthoimages, and digital surface/terrain models. The 3D meshes and point clouds are powerful tools to visualize the vineyard (Figure 11). Figure 14 shows a 2D rendering of the digital surface model (DSM) in grey scale. This figure also shows the location of two profiles taken using the open-source 3D point cloud program called Cloud Compare. Although these profiles are thick, this thickness represents the vegetation and crop rows (Figure 12).

Most importantly, the DSM is used to created topographic relief models in 2D or in 3D. These types of representations allow us to better visualize elevation change and the relative steepness of where vines are located (Figure 14 and Figure 15). The slope influences how water flows across a surface and penetrates the soil. Depending upon the soil type, structure, and stratigraphy we can make predictions on the direction and amount of water moving below ground.

AGRICULTURAL ANALYSIS

As mentioned in the introduction, the use of remote sensing techniques to indicate **plant health, plant vigor, and relative plant biomass** are well established using satellite and general aviation, however the transition to its application to UAS remains nascent (Sishodia et al. 2020). The use of UAS is part of the movement the agricultural industry calls “precision agriculture” whereby crops can be monitored periodically and compared to previous growth cycles to make predictions about its status.

Due to the technological advances in GPS location, vineyards can increasingly develop granular data sets, in some instances this can be narrowed to each plant, however data is generally analyzed by aggregates. Remote sensing allows farmers to quickly assess large areas that are followed by targeted field observations. In this manner, remote sensing becomes another tool to create more efficient crop management. In recent decades, UAS have provided farmers increasingly higher resolution data sets and there decreasing cost have allowed more small operations to make their own observations.

The power of the multi spectral sensor is that it captures each wavelength separately. This process allows these five light lengths to arranged mathematically. Each pixel can be added, subtracted, and divided. The combinations are used to create ratios in a range from -1 to 1. When a ratio is reviewed as a histogram, patterns are clearly visible that show which objects or features reflect light back into the sensor (Figure 16).

Many unique reflectance signatures have been identified and allow us to distinguish among features. Exposed soil has a relatively low value as compared with plant material that has a high signature. In a similar way, middle range values can help isolate shadows that contrast equally well in comparison to plants. As we shall see, certain formulas, combinations of bands, and calculations can highlight certain phenomenon.

In the analysis stage, we utilized two different GIS programs (QGIS and ArcMap), each can perform calculations with the multispectral images with the former being open source and the latter being subscription based. In total, we were able to create five of common remote sensing products useful in agriculture, each with their specific application, strengths, and weaknesses: CIR composite, Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge (NDRE), Green NDVI (GNDVI), and BIOMASS.

Use	CIR	NDVI	NDRE	GNDVI	Biomass
Plant health	x	x	x	x	
Yield potential		x	x	x	x
I.D. water bodies	x	x	x	x	
Soil moisture	x	x	x	x	
Soil composition	x	x	x	x	
Isolating Mask		x	x	x	
Classified	No	Yes	Yes	Yes	Yes

1. The **Color Infrared (CIR) composite** is used to quickly distinguish among common natural features like soil, water, and vegetation. It is not produced through a calculation, rather it is simply a product of replacing the Green band with NIR.
2. **Agricultural Indexes** are calculated by subtracting certain bands from others and dividing it by their sum to create a -1 to 1 index. The most commonly used is NDVI
    a) **NDVI -** *Normalized Difference Vegetation Index* $NDVI = \frac{(NIR-RED)}{(NIR+RED)}$

    b) **NDRE -** *Normalized Difference Red Edge* $Red\ Edge = \frac{(NIR-RE)}{(NIR+RE)}$

    c) **GNDVI -** *Green NDVI* $NDVI = \frac{(NIR-GREEN)}{(NIR+GREEN)}$

    These three formulas create different ratios of light primarily leveraging the non-visible, Red Edge and NIR, wavelengths. Plants tend to be most responsive in this spectrum since leaves strongly reflect instead of absorbing the non-visible light which allow for effective contrast to be generated. This phenomenon is created because plants absorb solar radiation in the visible light spectrum to produce energy during photosynthesis and tend to reflect longer non-visible wavelengths. The longer wavelength can overheat plants so plant cellular structures have evolved to reflect away way this potentially hazardous radiation

3. **Biomass** is calculated by using the total area represented by the crop in either of the three indexes above.

Color Infrared (CIR) Composite

The least complex and broadly useful indicator that can be created with multispectral bands is a Color Infrared (CIR) composite. This process does not require a formula or calculation, instead the normal ordering of the visible bands is altered. Color pictures are created by layering, like a sandwich, the Red, Blue, Green visible spectrums, yet when we rearrange and replace NIR at the top of the order followed by Red and Green (omitting blue altogether) a very distinct image is created which highlights the photosynthetic properties of plants. Instead of green being an indicator of vegetation, a vibrant red is in its place. As mentioned in the previous section, since the NIR is reflected by plants, this recombination highlights the reflective characteristics of NIR and allows for certain features to be accentuated.

The CIC allows for strong reflectance to be viewed as vibrant reds and weak reflectance in pink tones. This pink color range can be linked to unhealthy, water deprived, or struggling vegetation (Figure 15).

> "Unhealthy vegetation will reflect less in the NIR and appear as washed out pink tones, very sick or dormant vegetation is often green or tan, and man-made structures are light blue-green. Soils may also appear light blue, green, or tan depending on how sandy it is, with sandiest soil appearing light tan and clay soils as dark tan or bluish green." (MicaSense, 2021)

This deeply contrasting imagery can quickly illustrate broad characteristics of an area. For the purposes of agricultural analysis, CIC has its limitations. The image is a composite with each pixel representing an additive process among the three bands, unlike the next series of examples which are true indexes that can be manipulated mathematically. In contrast to the CIR composite image, an index is a number from -1 to 0. This allows categories to created which than can be grouped, classified, and mathematically manipulated. In the following sections we will see how this difference is significant.

NDVI (Normalized Difference Vegetation Index)

Normalized Difference Vegetation Index is the most common agricultural index. It uses the differences in intensities between the NIR and the Red bands to accentuate organic features and identify inorganic elements (Figure 19). The vineyard rows are clearly contrasted by the tilled soil, surrounding pathways, sidewalks, and asphalt roadways. This index defines values from -1.0 to 1.0. The values close to zero are primarily formed from asphalt, concrete, rocks, and bare soil which absorb some non-visible light. Very small values (0.1 or less) correspond to empty areas. Moderate values (from 0.2 to 0.3) represent shrubs and weeds, while large values (from 0.6 to 0.8) indicate cultivated plants which reflect non-visible light at high levels. This index can quickly show the distribution of dense, moderate, or sparse vegetation at any given moment.

This ability to distinguish among known reflection signatures allows for the vineyard rows to be isolated from the other elements of the topography. In this manner more granular analysis can be performed that are focused solely upon the cultivated areas. In Figure 20 the surrounding terrain and shadows are removed, leaving only the values represented by the vineyard. By reclassifying these remain values a more useful image emerges which focuses our attention on how only the rows are absorbing and reflecting Red and NIR light. For comparative purposes, a standardized distribution of values was chosen to view the data. Other methods might be more revealing, for example using a standard deviation, natural breaks, or geometrical interval, yet for month-to-month comparison a defined interval is being used.

The NDVI index does not measure chlorophyll directly, instead it observes how well a plant absorbs and reflects visible and non-visible light. When a plant is healthy it is more capable to photosynthesis and produce chlorophyll which requires the absorption of visible light and at the same time reflect non-visible light. In a similar way, if a plant is damaged, sick, lacking nutrients or water, or under siege from pests or disease, it is hindered and cannot absorb nor reflect certain wavelengths of light in the same way as healthy plants. When the RedEdge and NIR bands are compared a sharp increase occurs in the reflection coefficient further highlighting plant vigor (Boiarskii 2019). Since chlorophyll is produced by plants through the absorption of light as a food source, by association it is also an indicator of health.

Formula

- **NDVI -** *Normalized Difference Vegetation Index* $NDVI = \frac{(NIR - RED)}{(NIR + RED)}$

General Uses

- plant vigor
- differences in soil water availability
- foliar nutrient content (when water is not limiting)
- yield potential
- Eliminating soil and other nonorganic background layers

NDVI Assessment Maps

NDVI is useful to quickly assess the status of a cultivated area and identify general areas for further study. Initial assessments can be done visually however these are time consuming, difficult to conduct accurately, and performed consistently. To counteract these biases and create a quantitative data set that can more efficiently identify areas of interest, a zonal method was implemented. This involved demarcating specific areas, termed zones, that are based upon each row of vines or in the case of the heritage block, at the individual vine level. These georeferenced zones are than used to extract the values from the NDVI image. Once these are extracted than they can be further processed in a spreadsheet to be visualized as a chart or table.

Four assessment maps were created for each block of the vineyard. These show NDVI as five classes in a defined interval of 0.1 staring at a baseline of 0.5. The result are groupings as < 0.6, 0.61-0.7, 0.71-0.8, and >0.9. As mentioned previously, other types of groupings may be more illustrative, such as Natural

Breaks or standard deviation, yet for comparative purposes this method seemed appropriate to the task. The higher values in blue and green show high reflectance which is associated with healthy vegetation. In contrast the low reflectance in red and orange are associated with lower levels of chlorophyll production. The actual number does not necessarily refer to a specific vegetative condition since light will reflect onto the sensor in varying ways under different conditions, some of these are related to different times of the day, seasonal changes, cloud cover, and angle of the sun. The specific value number may be of less importance, instead it is the change in relative distribution of values which is more illustrative. The NDVI maps in association with the charts seems to provide a useful analytical gaze to recognize patterns and critically assess differences. These maps can be used to identify areas for follow-up with field observations.

For each of the blocks, except for the heritage block, a comparison was made between the June versus July observations. As we shall see below this 30-day difference was very illustrative since certain areas did show shifts in the data while others remained consistent. From a technical point of view, the consistency indicates that our methods in capturing the data are working. We can make repeated observations with uniform results. This allows us to better identify the areas which are exhibiting noticeable change.

In the future, it may be very revealing to further parse a sample of rows into vine level zones to provide an additional window into how each plant is growing in relation to others and further focus our attention. To georeferenced and isolate each vine will be an easy exercise when the vines are in their dormancy period.

NDVI – South Slope Block

The South Slope Block NDVI row values were more varied of the main vineyard. This is not necessarily surprising since it is the largest of the four blocks, has the most diversity in varietals, and the most variation in slope aspect. As a whole, the block seems to have overall increased mid-range values and decreased low-range values from June to July (Figure 21).

Specifically, the NDVI graph shows well performing area in rows 15 -25 and 61-70, the former can be linked to an overwatering event. In June, there were many rows, 1-14 and 26-60 which showed low values. In comparison to July, a large portion of these rows, 1-14 and 26-40, seemed to strengthen in the mid values. It does seem that there was a reduction in low values over all from June to July.

These row values can be further parsed and examined, for example row 12 seems to exhibit a signature unique to others and may be a candidate for a field observation. In general, this is a comparative method that is relative to its position and timing.

NDVI – East Slope Block

In contrast to the South Slope Block, there is little variation between the June and July observations (Figure 22). Instead, the East Slope Block seems to be on a relatively consistent growth trajectory. A few groupings of rows, 30-36 and 1-5, have slightly higher values. These show the consistent presence of values above 0.9 with row 20 expressing higher than most. Only two rows, 9 and 22, are outliers and exhibit a wider breadth of low and mid-range values. This is surprising given that these seem to be dense in canopy and adjacent vigorous rows.

NDVI – Hilltop Block

In comparison to the other blocks, this is the most consistent with very little variation between June and July. Although the block as a whole has not changed significantly, there are two areas that can be highlighted. The first are rows 14 -17 which seem to have a more dispersed representation of the mid to low values in comparison to the entire block. These are the four most northern rows. In contrast, row 12 seems to be the more vibrant and vigorous of the block. Apart from the aggregate values, the image shows visible thinning and low values in rows 3-4 and 6-7 located in the western area. These are highlighted with grey oval dashed lines in Figure 23.

NDVI – Heritage Block

The heritage block is unique since the zones represent each individual vine and are not an aggregated like the other blocks. This allows a granular view into the growth and development of a single vine. Overall, there is considerable variation among the values (Figure 24). Some of this is caused by the proximity and overlap of adjacent olive trees, however much the difference occurs within the rows. Some vines are relatively vigorous, namely 81 and 82. These are extending well into adjacent zones while others to be seem atrophied. The chart can easily identify specific vines which exhibit extremely limited growth, 44, 51, 97 and 101. Certain groups of vines seem to have values that contrast their counterparts. For example, 82 and 83 have large canopies and vigor, while 101-105 seem to be or smaller size and lower values.

Biomass

By isolating certain NDVI values from others, a relative sense of plant biomass can be estimated. This is less about a total mass and more about the total leaf area of the canopy. It is not able to estimate density nor weight as in the common notion of “mass”, however it can be a useful tool for crop management. Biomass is measured in square meters and is easily calculated. When measured over time it provides an approximate rate of growth (Lamb 2000, Hall et al. 2002). Biomass can be a predictive tool when data is compared with previous years, weather conditions, and irrigation methods. It also can be useful to show the efficacy of intervention methods, for example, if irrigation is interrupted then restarted, the impact of both effects can be visualized.

In the two observations made in June and July, there is a notable increase in leaf canopy. This allowed for some preliminary images and charts to be created:

1) a visual representation of the increase in foliage
2) total area change from June and July
3) the percent increase from June to July.

Each are useful to quickly identify areas which may require attention. The main image shows the limits of June growth superimposed upon the dark green extension captured in July. The growth is visible however it is not easy to interpret. The graphical representations allow for clearer patterns to emerge. These calculations are approximated and in future work the implementation of permanent georeferenced ground control points will increase accuracy.

Biomass East Slope Block

The rows in the east slope are more consistent in size than the other block, yet some rows do seem to outperform others even they are of similar size as adjacent rows (Figure 25). Rows 25-24 and 19-18 stand out in both months with more than double the area being generated. In terms of productivity, there are many which show a 30% to 45% increase (35-33, 19-18, 5-1) in the June to July four-week period, and some seem to be slightly less productive, <15% (27-26,17-16, and 8).

Biomass South Slope

In terms of total area, unadjusted for row size, Rows 16-24, 34-40, and 61-63 stand out from the adjacent rows (Figure 26). These seem to be denser and more completely fill the inner row way. Regardless of row length, there are many which show a 60% increase in a four-week period and some which seem to be slightly less productive, less than 15%. Interestingly, some of the shortest rows located at the rows constricted western end of the block have some of the highest productivity levels in comparison. In a similar surprise, the rows which experienced an over irrigation due to a valve failure seemed to be the most vigorous in June, yet after the valve issue was resolved the adjacent rows rebounded with higher productivity.

Biomass Hilltop

As expected, there is variation among the rows in terms of total canopy area (Figure 27). Rows 13 is the lowest in relation to its neighbors, however it did have an impressive amount of growth from June to July. In contrast row 1 is the bulker than rows of similar size and kept pace ahead in July. Overall, many rows show a 30% to 45% increase in a four-week period and some which seem to be slightly less productive, less than 5%.

Normalized Difference Red Edge (NDVE)

Another commonly used agricultural index is the Normalized Difference Red Edge (NDVE) which in also leverages the non-visible spectrum to better visualize chlorophyll content. In a similar manner as NDVI, the NDVE uses another narrow spectrum of non-visible light, Red Edge, in a ratio instead of the visible Red band that is used in NDVI. The advantage of Red Edge is that the wavelength is shorter (centered around 715 nm) and is absorbed more that the longer wavelength of Infra-Red (centered around 842 nm). Red Edge also has an advantage over red light during middle to late growth phases. As leaves grow rapidly, chlorophyll accumulates which tends to block red light absorption, in contrast the Red Edge band is better able to penetrate (Boiarskii et. All 2019). Chlorophyll saturation can create limitations for NDVI. This means that using multiple indexes during the growth cycle of the plant is more efficacious than relying on one index.

It has been difficult to identify peer reviewed research about the use NDVE in viticulture. In a brief search and review of articles, it seems that NDVI is the standard for analysis, however as mentioned below there may be some promising results in other crops.

> "With NDRE we observed crops with low chlorophyll content, indicating nitrogen limitation in the leaves. These observations demonstrate the efficacy of using NDRE as a sensitive index for monitoring chlorophyll content. Therefore, we propose that different indices may be most useful for different crops, plant density, seeding rates and growth stages." (Boiarskii et. All 2019)

The above study utilized a similar UAS configuration as this project, although the crops were distinct (soybean, fodder crops, and cedar seedlings) the results were encouraging. Given the lack of research of NDVE and viticulture, this maybe an area for study, collaboration, and publication.

Formula

- **NDRE -** *Normalized Difference Red Edge* $Red\ Edge = \frac{(NIR - RE)}{(NIR + RE)}$

Comparative Challenges

It would be informative to compare the NDVI and NDVE, however the range for each are unique. NDVI has a grouping of values between the 0.5 to 1.0 versus a lower range in NDVE from 0.1 to 0.6 (Figure 28). A unique classification

NDVI/NDVE Comparison

All four blocks were compared to better understand the relationship between the two indexes and if NDVE might highlight certain areas that are not apparent in NDVI (See). Since these two indexes are focused on two different light combinations, the values themselves are less important than their distribution between low to high.

There is a general symmetry of values between the two indexes. The midrange values for each index tend to align, however there are individual rows and groupings which tend to deviate from this pattern. In the East Slope Block, rows 36-31 have slightly elevated low values not seen in other rows and are arranged in a pattern that is not mimicked in NDVI. Rows 20-19 show a range that seems inconsistent with adjacent rows and with NDVI.

In the South Slope Block, a similar pattern as the East Slope occurs in rows 51-24, where there is an elevated range of low values which do not necessarily match NDVI. Rows 70-61 show alternating values in NDVI, yet in NDVE the values are more flattened and consistent. The application of NDVE for viticulture may not be apparent now, although continued monitoring throughout each of the growth stages may prove fruitful in the future.

Green Normalized Difference Vegetation Index (GNDVI) - Green NDVI

In a similar manner as NDVI, this index is created with Green light instead of Red light. It is commonly used as a management tool for crops to indicate stress and general health. Industry websites tend to promote the advantages over NDVI with ability to observe nitrogen retention and relative moisture:

> "GNDVI has wider dynamic range than NDVI and is, on average, at least five times more sensitive to chlorophyll-a concentration. (MicaSense, 2021)
>
> " The Green Normalized Difference Vegetation Index (GNDVI) is a vegetation index for estimating photo synthetic activity and is a commonly used vegetation index to determine water and nitrogen uptake into the plant canopy." (Esri, 2021)
>
> **"**This is an indicator of the photosynthetic activity of the vegetation cover; it is most often used in assessing the moisture content and nitrogen concentration in plant leaves according to multispectral data which do not have an extreme red channel. Compared to the NDVI index, it is more sensitive to chlorophyll concentration. It is used in assessing depressed and aged vegetation." (Soft Farm, 2021)

The application of GNDVI for viticulture is unclear, however like NDVE, it easy to calculate and compare with other indexes. Like NDVE, it has a unique range of values which need to be classified differently than the other indexes. For the purposes of this test a 0.5 interval was used to create a series of charts for comparison.

Formula

- **GDRI** – Green NDRI

$$GNDVI = \frac{(NIR-Green)}{(NIR+Green)}$$

THE CHALLENGE OF INTERPRETATIONS

This report is less about explaining why certain values are different than others and more about how we can present these values in a manner that is useful for the experienced vintner and vineyard manager. Since this is the first time we have carried UAS remote sensing, we actually have very little data to make comparisons. If there is one lesson learned, is that agricultural analysis relies upon the comparative process, meaning that there is not necessarily an optimal number which determines which plant is healthy versus unhealthy, instead spectral signatures must be compared within groups of crops that are imaged at the same time.

This comparative aspect is important to recognize, since agricultural assessments are more accurate when there is a significant amount of previously data that was captured under similar conditions, and at the same point in the growth cycle. To complicate matters further, it has been observed that it can be difficult to draw accurate comparisons among different closely associated block:

> “Recent work (Bramley 2001) has demonstrated that considerable spatial variation exists with quality indicators such as color and total phenolics across individual vineyards.” (Lamb 2004)

As mentioned previously, this report should be seen as a starting point and form the basis for how we might consider developing our practices as we move forward.

Spectral values will change dramatically as the plant moves through its growing cycle. At different points there will be unique data points to document and track, in the dormant stage a base line for the overall size of each individual plant can be approximated and the number of buds per plant may be observable (Figure 34). In the growing stages, the ever-increasing size of leaf canopy can be tracked. For red grape varieties, there is increasing research into how remote sensing can indicate the yield potential of grapes (Ledderhof et. 2015).

It is strongly recommended that a monthly practice is implemented that will continue to capture images over the entire season and beyond (Figure 34). This will provide the basis to form more meaningful conclusions. It will also provide more meaningful data to better align our classification methods, it may be the case that classification will shift throughout the growing cycle.

The strength of our interpretations is limited by the dearth of data, other data points, and the testing of formalized research questions. This report focuses upon reflectance values and does not make attempts to draw comparisons with other measurements which could be observed in the field: leaf pressure chamber tests, vine trunk circumference, soil electrical resistivity, and harvest quantity and quality. There is a wide range of research that leverages airborne imagery. Many of which could be replicated or tested in unique manners that may be inspiring, conducted by our students, and form the basis for short and/or long term research.

CONCLUSION

Our first series of flights are undoubtedly a success! We were able to repeatedly capture data, process this data, and make thoughtful observations. Most importantly, aspects of this work are already being used by Viticulture & Winery Technology program. Relatively quickly, a new map of the vineyard was created for marketing and as an educational resource (Figure 1). Students have witnessed the UAS in flight as part of an in-class demonstration during the 2021 summer session.

This effort set out to explore

- What images and reports can be produced from the data?
- How can we accurately interpret the data?
- Which images and reports are the most useful for viticulture managers?
- What is the overall health of the vineyard?
- Can we explain why certain areas differ as compared to others?

As expected, the high-resolution imagery has provided detailed topographical 2D and 3D surface relief models. The topography for the vineyard is already well understood, however having a data set showing features such slope and elevation change will be useful in the classroom and the field.

The multispectral images and resulting agricultural indexes are equally impressive, however require much more preparation and training to interpret. The agriculture indexes were able to highlight certain areas that seem to differ than their counterparts, however this data is quite removed from its context. It remains to be seen whether these variations are related to specific ongoing issues and whether these are of any actual concern. It may be the case that some of the variation is not caused by current processes but are the result of previous events.

One clear limitation to this report is the lack of contextualization of these findings within the current management practices and the longer more robust history of the vineyard. The interpretation of this unique data set should be considered preliminary and reflective of our current level of experience. It is expected that future versions will be different. The challenge moving forward will be to develop ways to integrate this new information into curriculum and vineyard management practices.

Most importantly, to use this data set effectively requires follow-up work in the vineyard. This would involve conducting a series of targeted field observations in areas identified in the images. This implies that a system for accounting and documenting the types of field observations

Lastly, this report has been written more as a narrative about how we went about conducting micro-remote sensing work in the vineyard, than about a comprehensive discussion about the health of the vineyard. Instead, it has laid out a series of steps that were taken to better familiarize ourselves with the process. For students who might be asking the following questions, it may provide a glimpse of a future pathway:

- *Can this be a profitable venture for me?*
- *What are the different aspects necessary to learn?*

LESSONS LEARNED

What did we learn? What area might our staff and students in the future explore? In general, the use of the UAS is relatively easy to set-up, fly, and capture data. The data capture process can be learned in a relatively short amount of time. The data processing is more involved and requires more advanced training in GIS, which LPC does offer courses. Below is a list of lessons learned with their respective page references.

Flight Preparation

- Use contour adjusted flight paths for topographic areas (9).Testing Different Flight Routes
- Investigate alternative flight planning software options (9).
- Increase comparative accuracy by installing ground control points around the vineyard (17).

Additional Type of Flights

- Test lower altitude flights to better measure where pixel resolution suffers (11).

Additional GIS Processing

- Create test micro zones at the vine level for the larger blocks (11).
- Geo-reference each vine during dormancy (15).
- Test different classification methods for better seasonal comparisons (21).

Field Observations

- Develop a process to make periodic field observations using existing equipment (21).
- Create a document record system in coordination with the remote sensing data (21).
- Include of climatology into future reporting (21).

FUTURE PATHWAYS

Throughout this process many ideas and questions arose which might help aim the trajectory of this work. Most prominently it showed our own limitations in learning the current state of research for vineyards using UAS. Prior this work we had not fully appreciated the breadth of academic journals and industry resources. It would be useful to create a list of these and professional organizations for students and as conferences for ongoing professional development.

Additional Resources, Training, Education,

- Develop an annotated bibliography of current methods and advancements
- Publish a list of resources, professional organizations, and academic programs

Secondly, in coordination with our career program, we can begin discussions with companies who are doing UAS remote sensing for vineyards. As educators we need to know the level of training and experience level necessary for our students. In the same way, we can also make more formal interactions with vineyard operators about how UAS is or could be useful in their work.

Community Outreach

- Interview UAS companies about their practices and internship possibilities for our students
- Identify vineyards who may be interesting in partnering with LPC.

In the same vein as above, it would be in our best interest to create discussions about how vineyards use the data. How might they envision a report? What might they see as important? Can we offer them training at any specific level which may be necessary? This report was a first attempt at understanding the process, however only in a relationship with others can we continue to prosper and learn.

Report Presentation

- Interview vineyard managers to better understand their needs.
- Explore alternative ways data can be made available to the public?
- Better contextualization of data in relation to past processes.
- Would a stripped down “mini-report” be a more useful reporting format?

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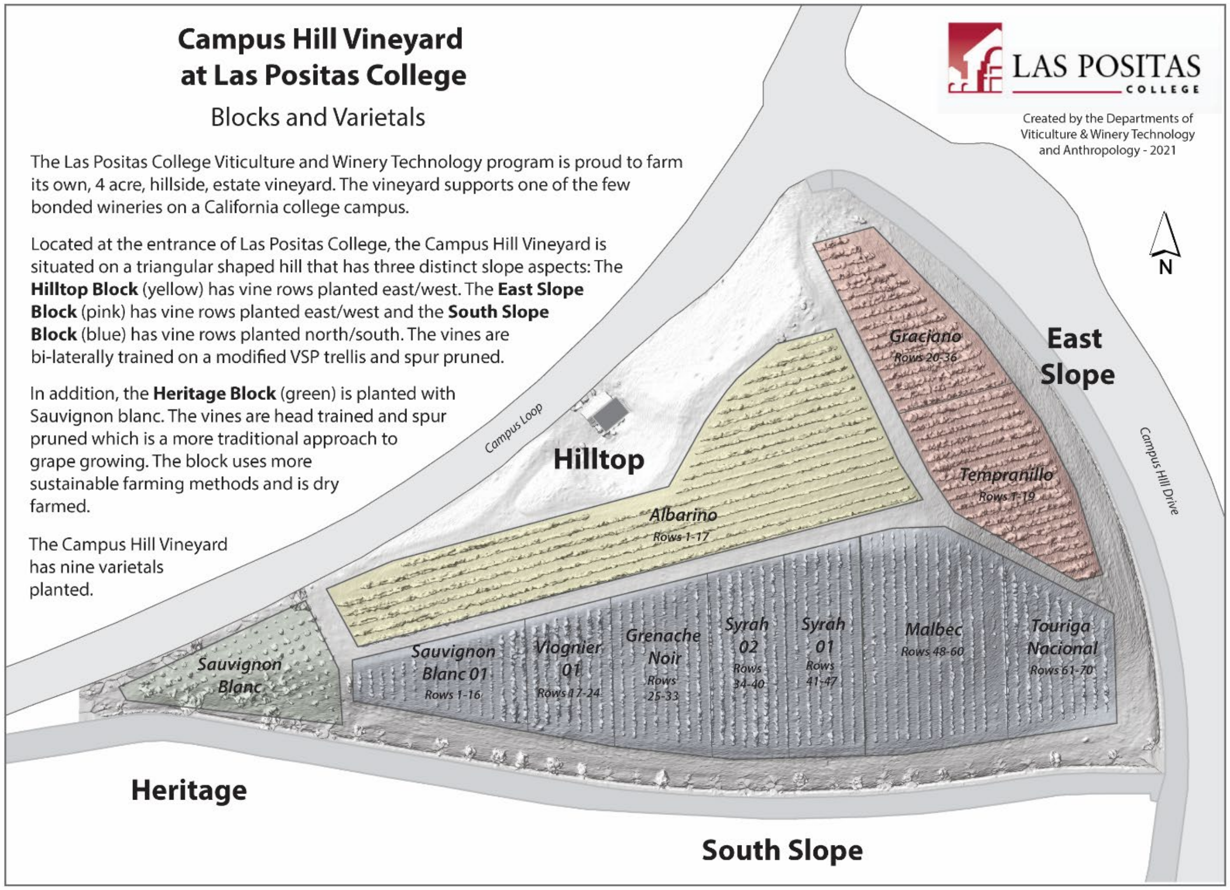
Appendix - Figures



Campus Hill Vineyard at Las Positas College

Blocks and Varietals

The Las Positas College Viticulture and Winery Technology program is proud to farm its own, 4 acre, hillside, estate vineyard. The vineyard supports one of the few bonded wineries on a California college campus.

Located at the entrance of Las Positas College, the Campus Hill Vineyard is situated on a triangular shaped hill that has three distinct slope aspects: The **Hilltop Block** (yellow) has vine rows planted east/west. The **East Slope Block** (pink) has vine rows planted east/west and the **South Slope Block** (blue) has vine rows planted north/south. The vines are bi-laterally trained on a modified VSP trellis and spur pruned.

In addition, the **Heritage Block** (green) is planted with Sauvignon blanc. The vines are head trained and spur pruned which is a more traditional approach to grape growing. The block uses more sustainable farming methods and is dry farmed.

The Campus Hill Vineyard has nine varietals planted.

Created by the Departments of Viticulture & Winery Technology and Anthropology - 2021

Figure 1 - Campus Hill Vineyard: blocks and varieties

Figure 2 - Satellite image showing Las Positas Campus (Google Earth).

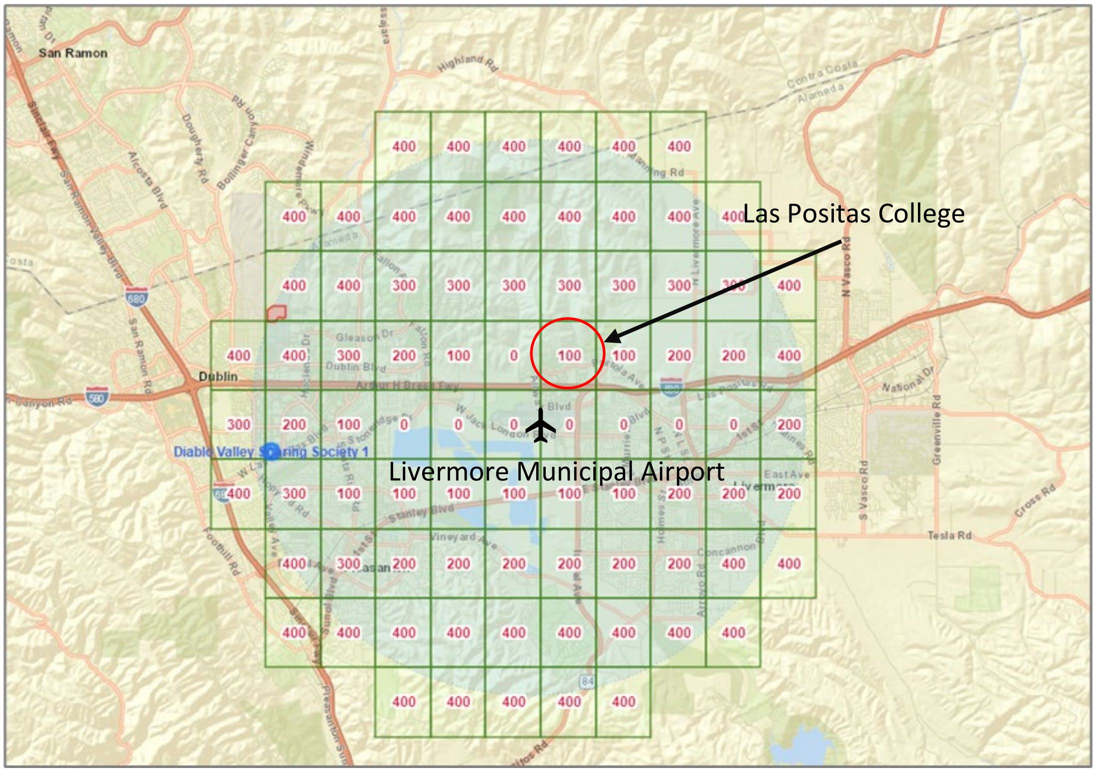
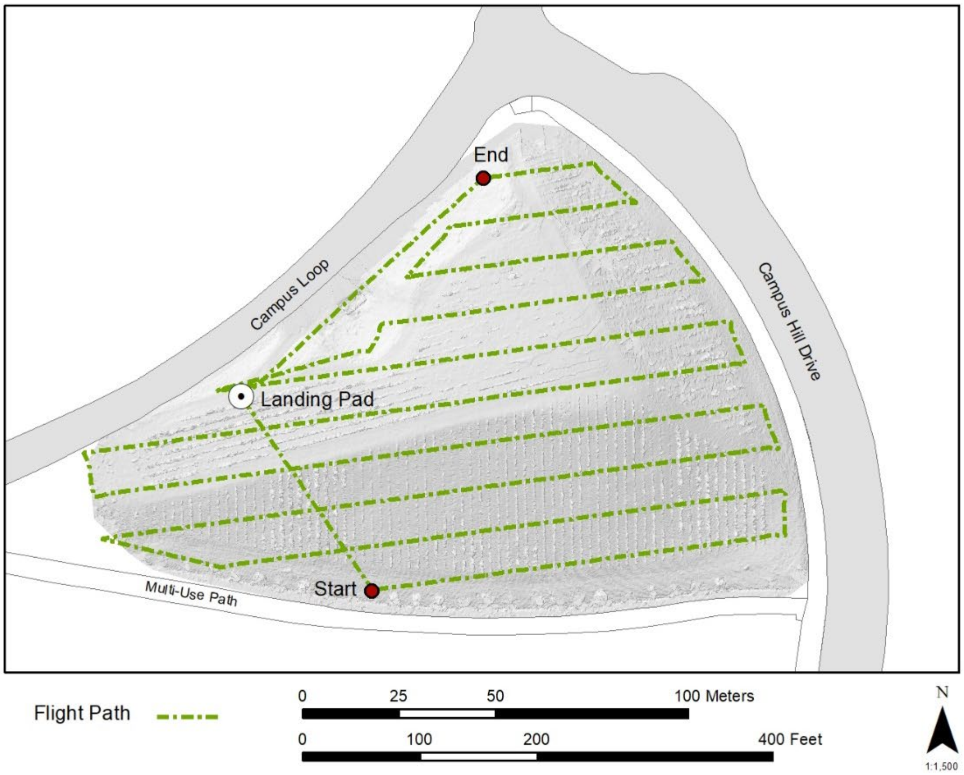


Figure 3 - Overview of the FAA controlled airspace (Class D) around Livermore Municipal Airport.

Figure 4 - Close-up of the UAS elevation restrictions (red numbers) above Las Positas College.



This map represents the flight path of the Line Survey. At the lower elevations, the overlapping coverage of the sensors was excellent, however at the peak overlap was spotty. In future flights, the pathways will be narrowed to compensate.

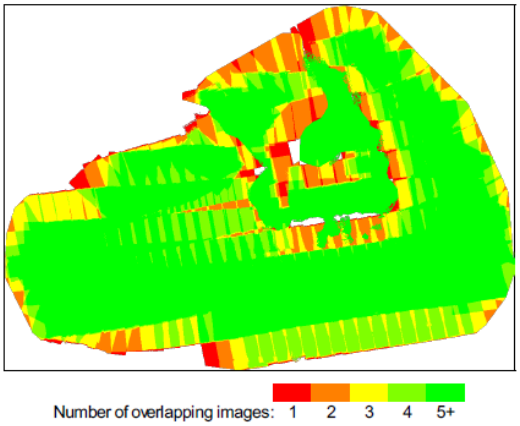
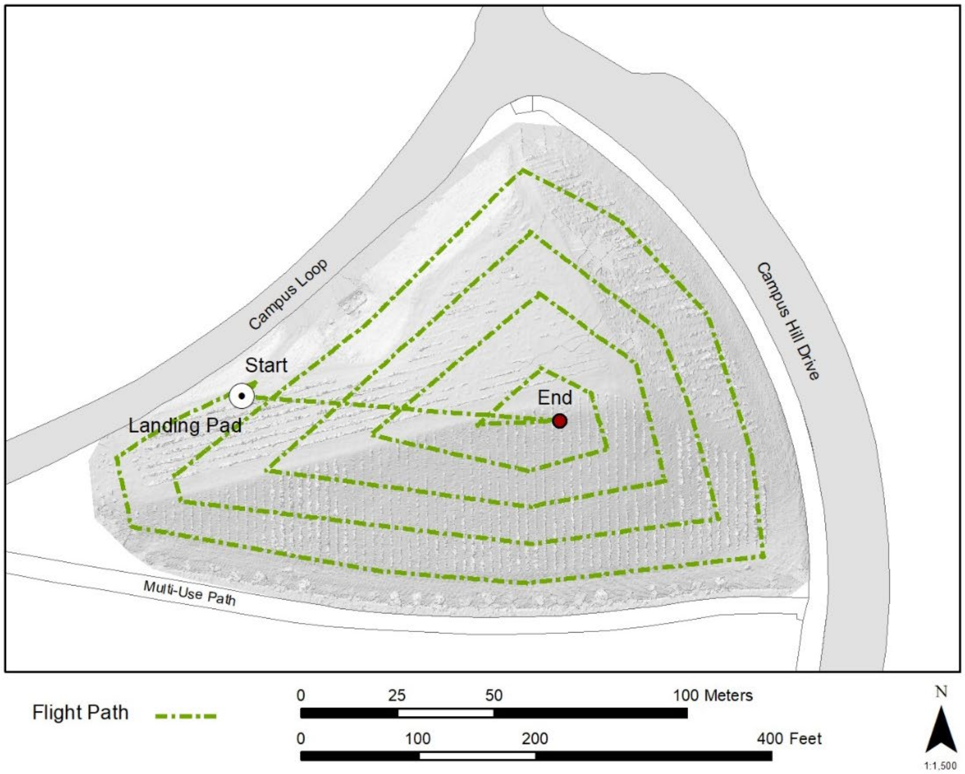


Figure 4: Number of overlapping images computed for each pixel of the orthomosaic.
Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Figure 5- Line survey flight path and overlap.



This map represents the flight path of the Spiral Survey. It is suggested that agricultural surveys are conducted at similar elevations. This does require more advanced flight planning, yet as a simple work around, a spiral survey mimics this pattern. At the lower elevations, the overlapping coverage of the sensors was excellent, however in the area north of peak overlap was spotty. This was due to wide

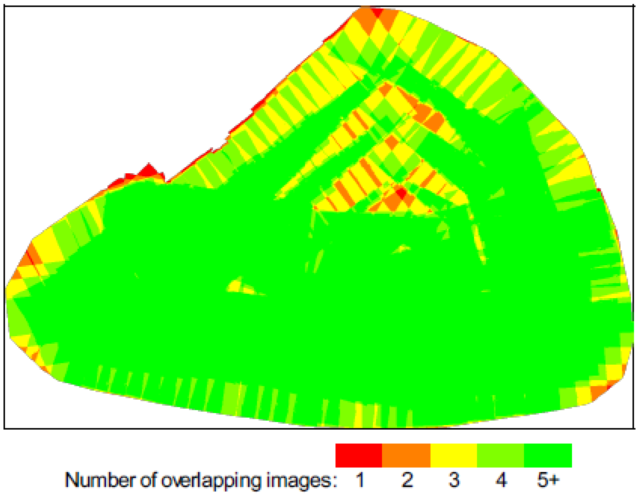
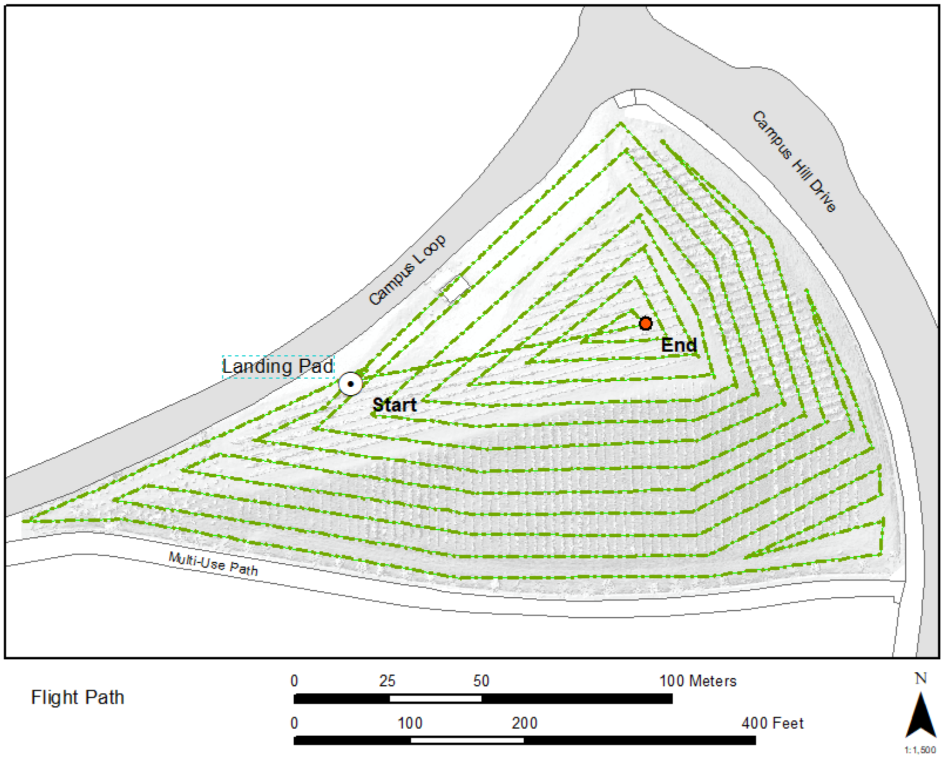


Figure 4: Number of overlapping images computed for each pixel of the orthomosaic.
Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Figure 6 - Overlap report of first spiral survey pattern



This map represents the third flight path using a Spiral Survey. This was a great improvement from previous tests. The transects are much closer together allowing for increased overlap of images. It expands coverage to include the heritage block and associated olive trees. The path follows the elevation contour, so all images are collected in a similar 30m above ground level. Although there is more distance traveled, the speed was nearly doubled minimizing flight time to a single battery pack.

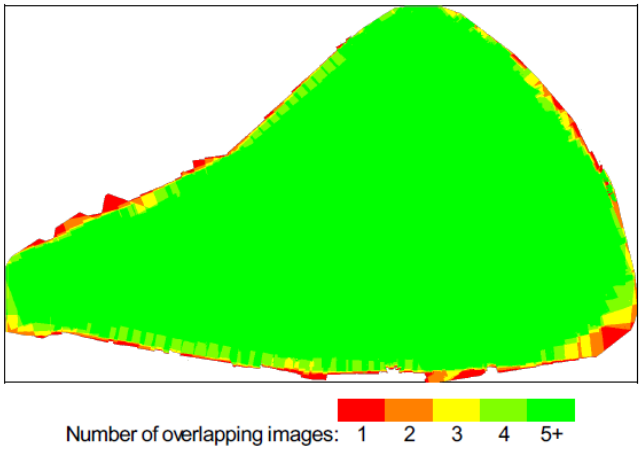
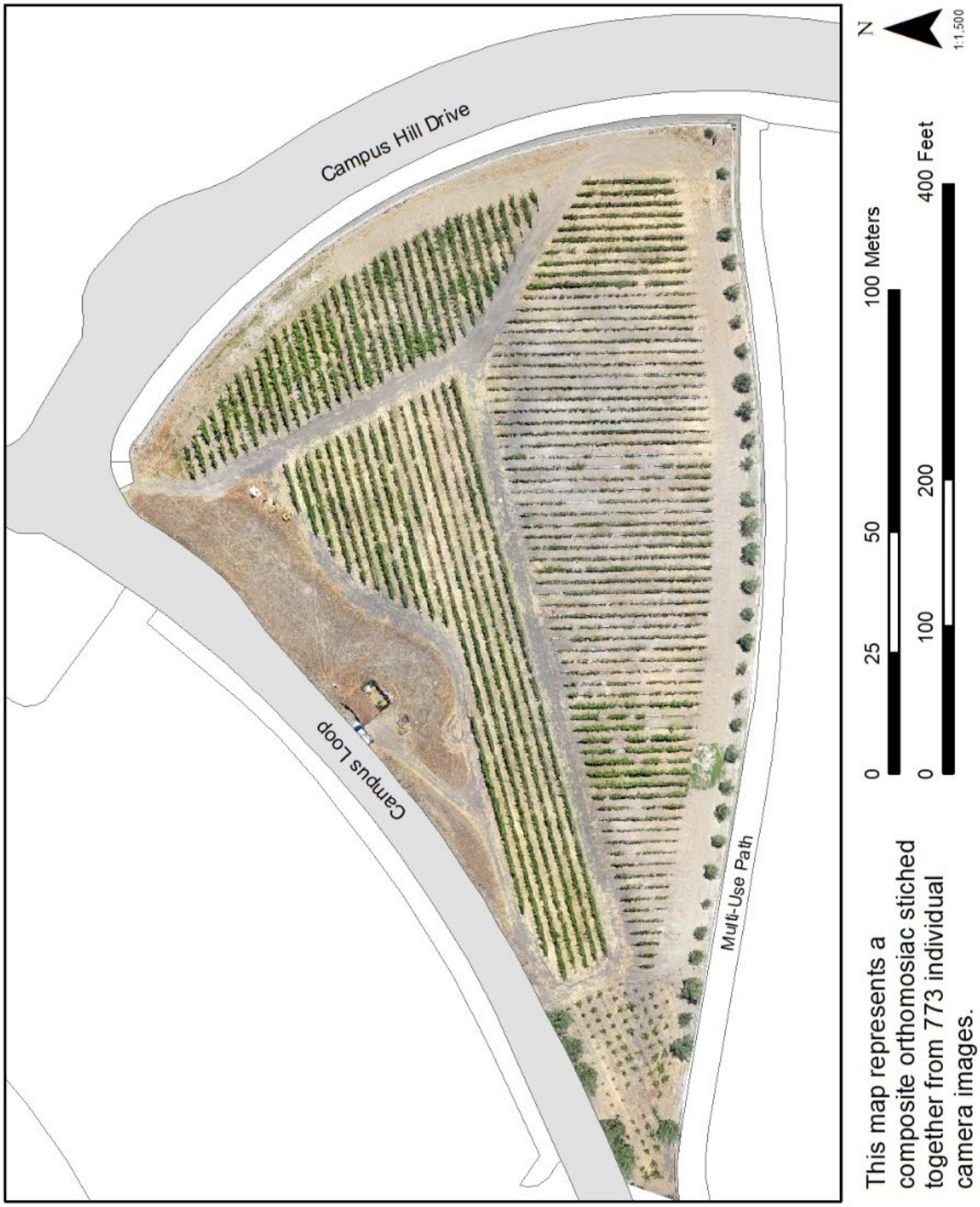


Figure 4: Number of overlapping images computed for each pixel of the orthomosaic.
Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Figure 7 - Final flight path test



This map represents a composite orthomosiac stiched together from 773 individual camera images.

Figure 8 - Orthomosiac

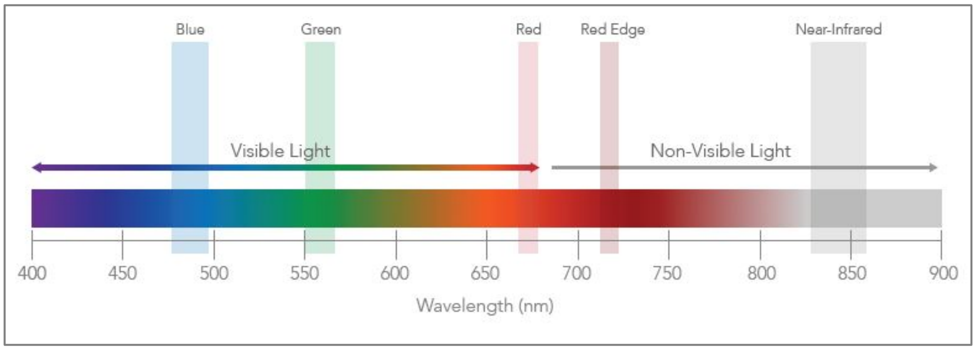
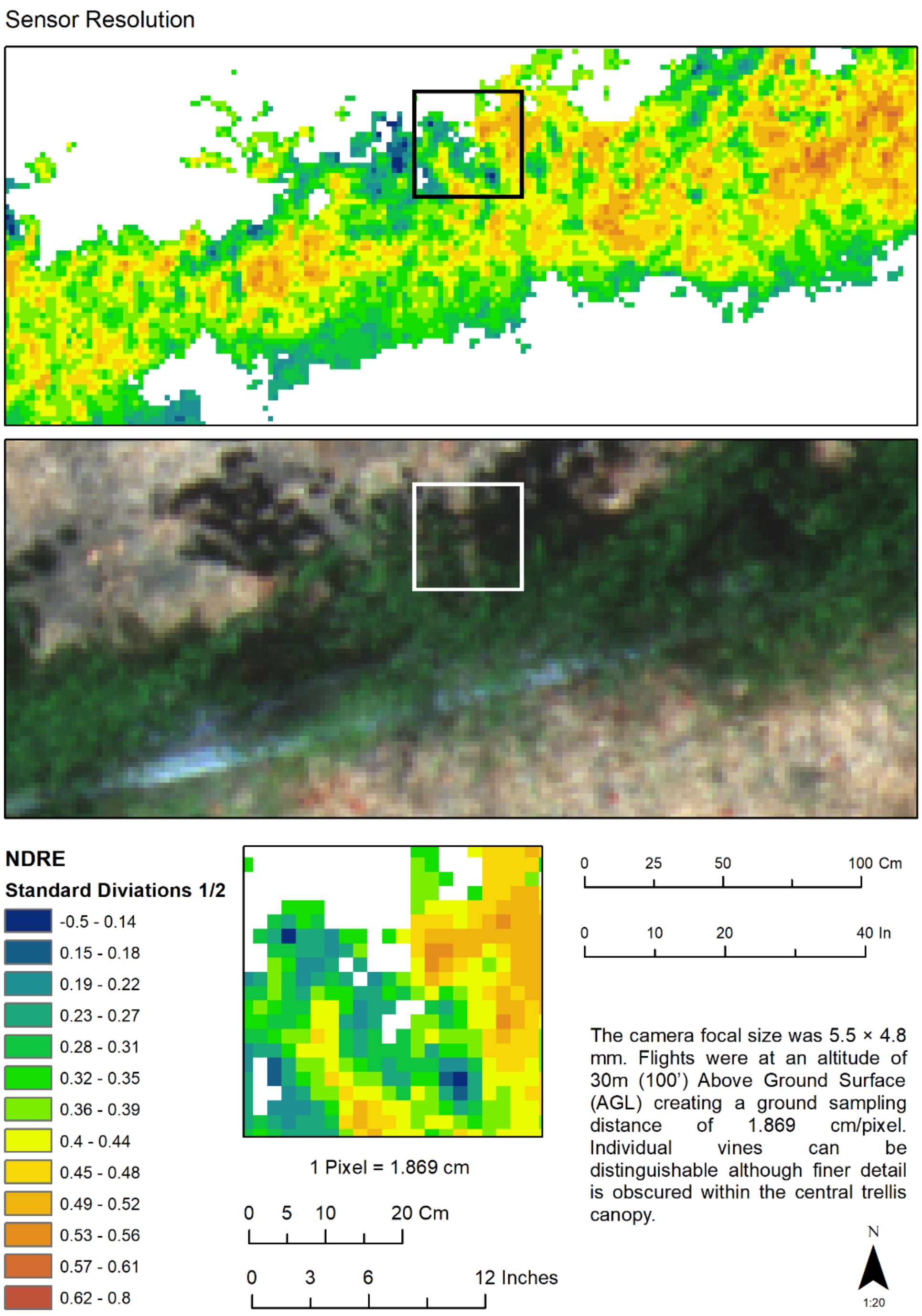


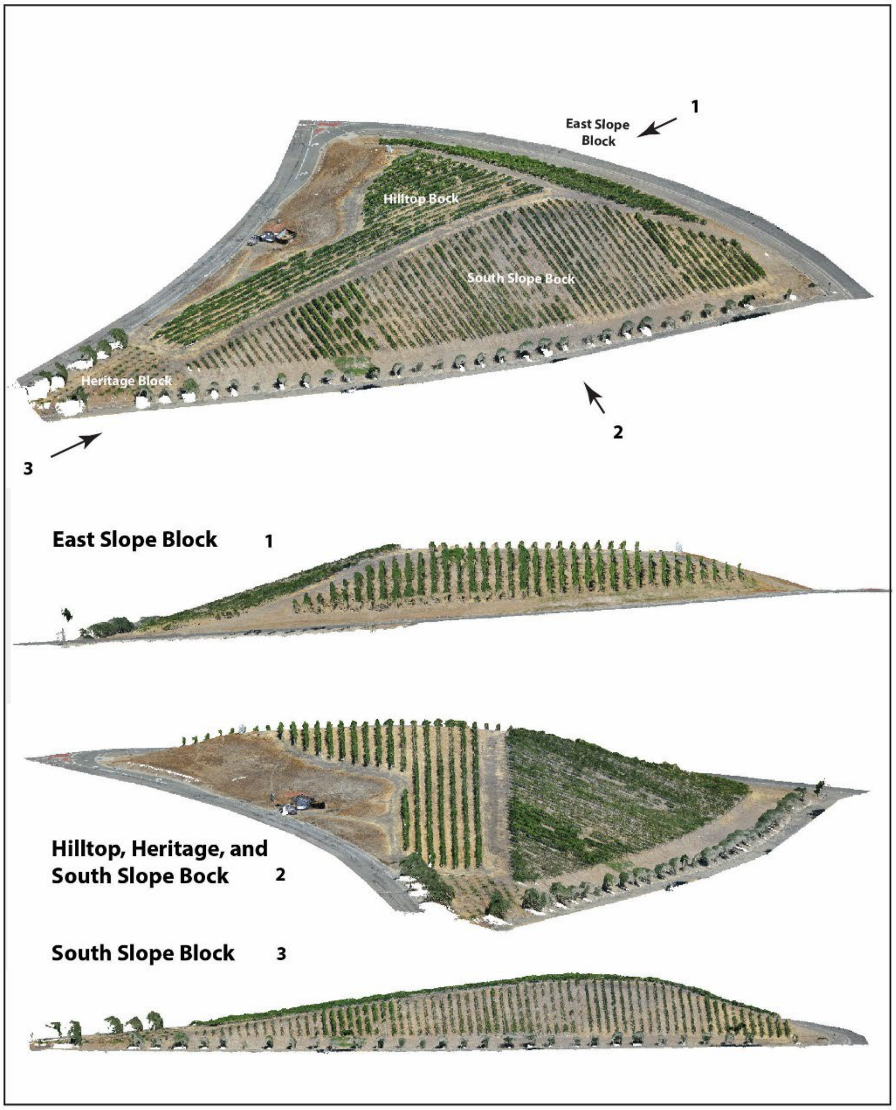
Figure 9 - Wavelength chart



The camera focal size was 5.5 × 4.8 mm. Flights were at an altitude of 30m (100') Above Ground Surface (AGL) creating a ground sampling distance of 1.869 cm/pixel. Individual vines can be distinguishable although finer detail is obscured within the central trellis canopy.

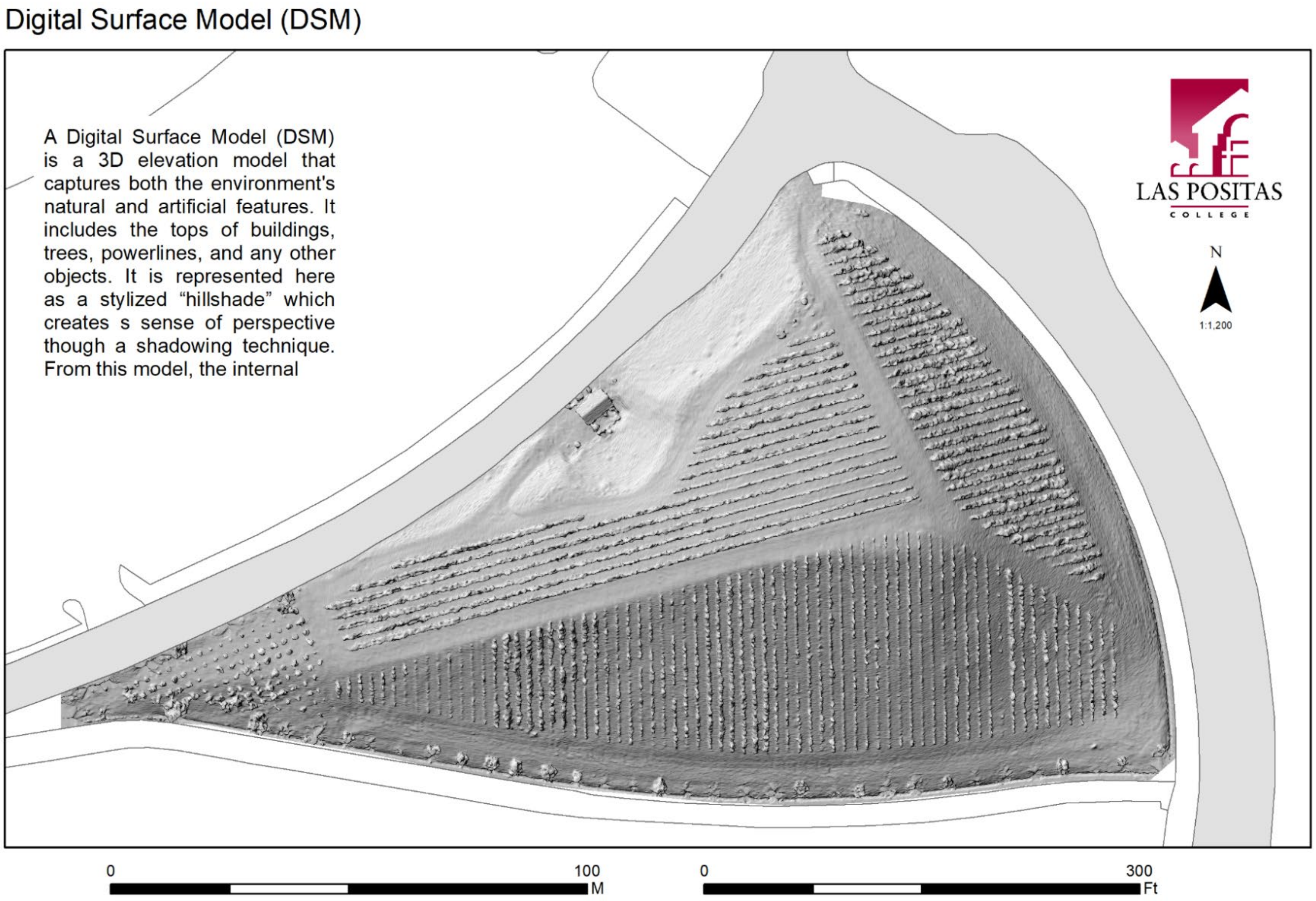
Figure 10 - Sensor resolution

3D POINT CLOUDS



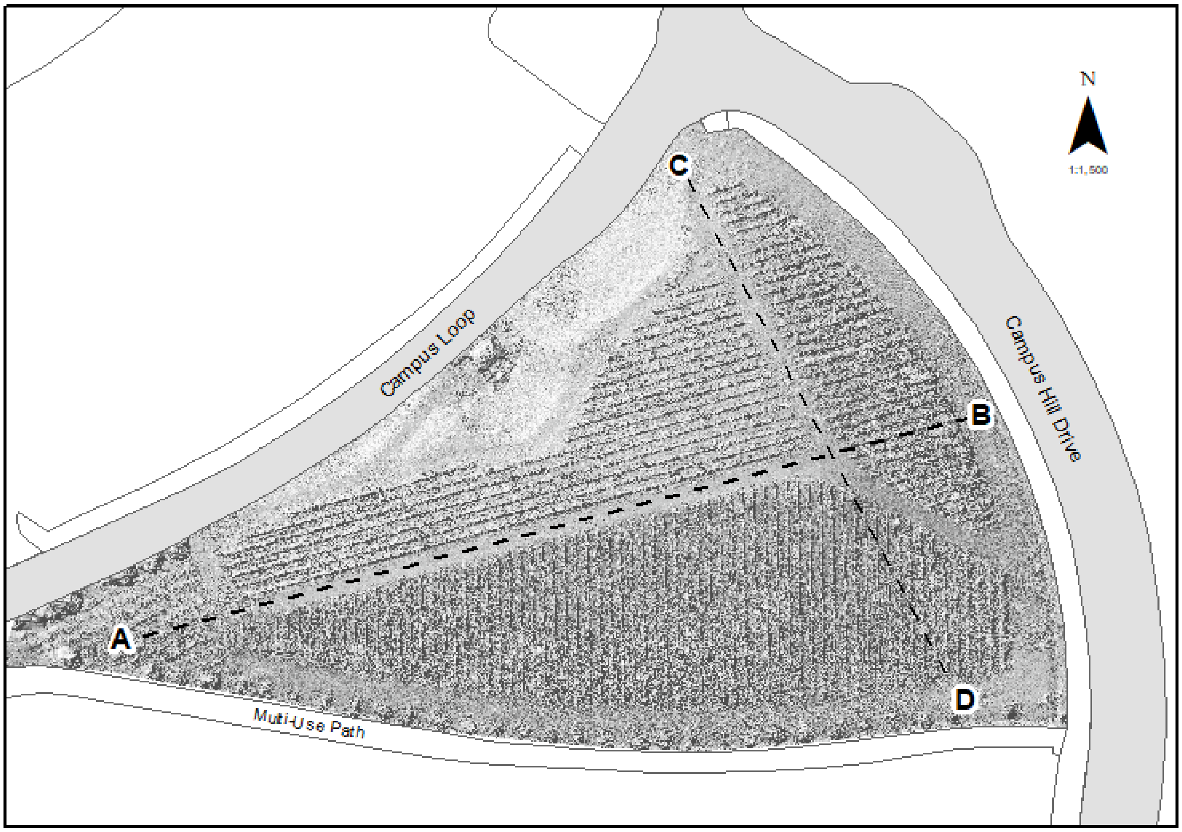
The 3D point clouds are powerful tools to visualize the vineyard from multiple perspectives. These three profiles below were created using the open-source 3D point cloud program called Cloud Compare.

Figure 11 - 3D Point cloud rendering


Digital Surface Model (DSM)

A Digital Surface Model (DSM) is a 3D elevation model that captures both the environment's natural and artificial features. It includes the tops of buildings, trees, powerlines, and any other objects. It is represented here as a stylized "hillshade" which creates s sense of perspective though a shadowing technique. From this model, the internal

Figure 12 - Digital Surface Model (DSM)



This map represents a 3D digital surface model (DSM) in 2D. The two lines represented as AB and CD are profiles that were extracted and shown below as 2D cross sections of the vineyard.

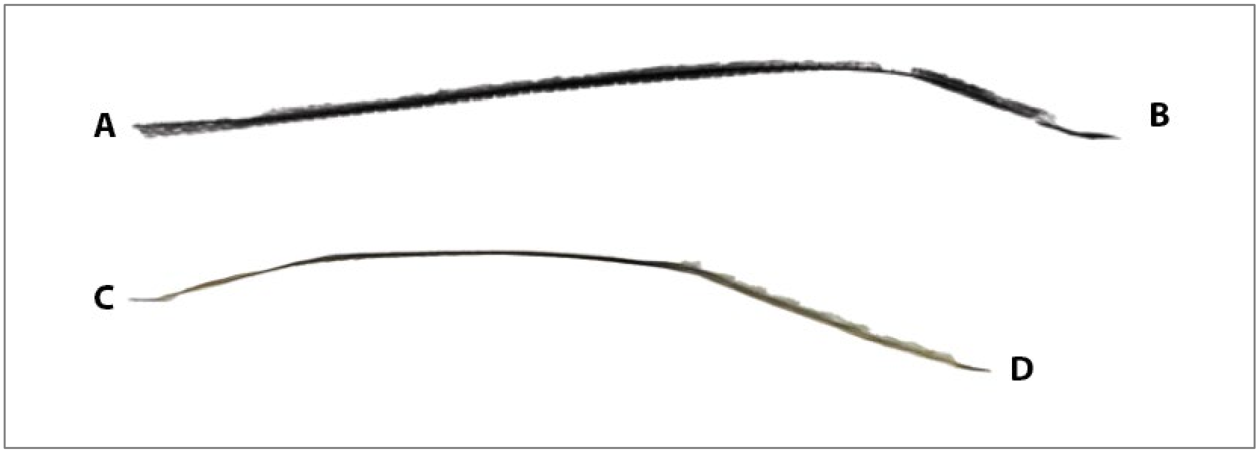
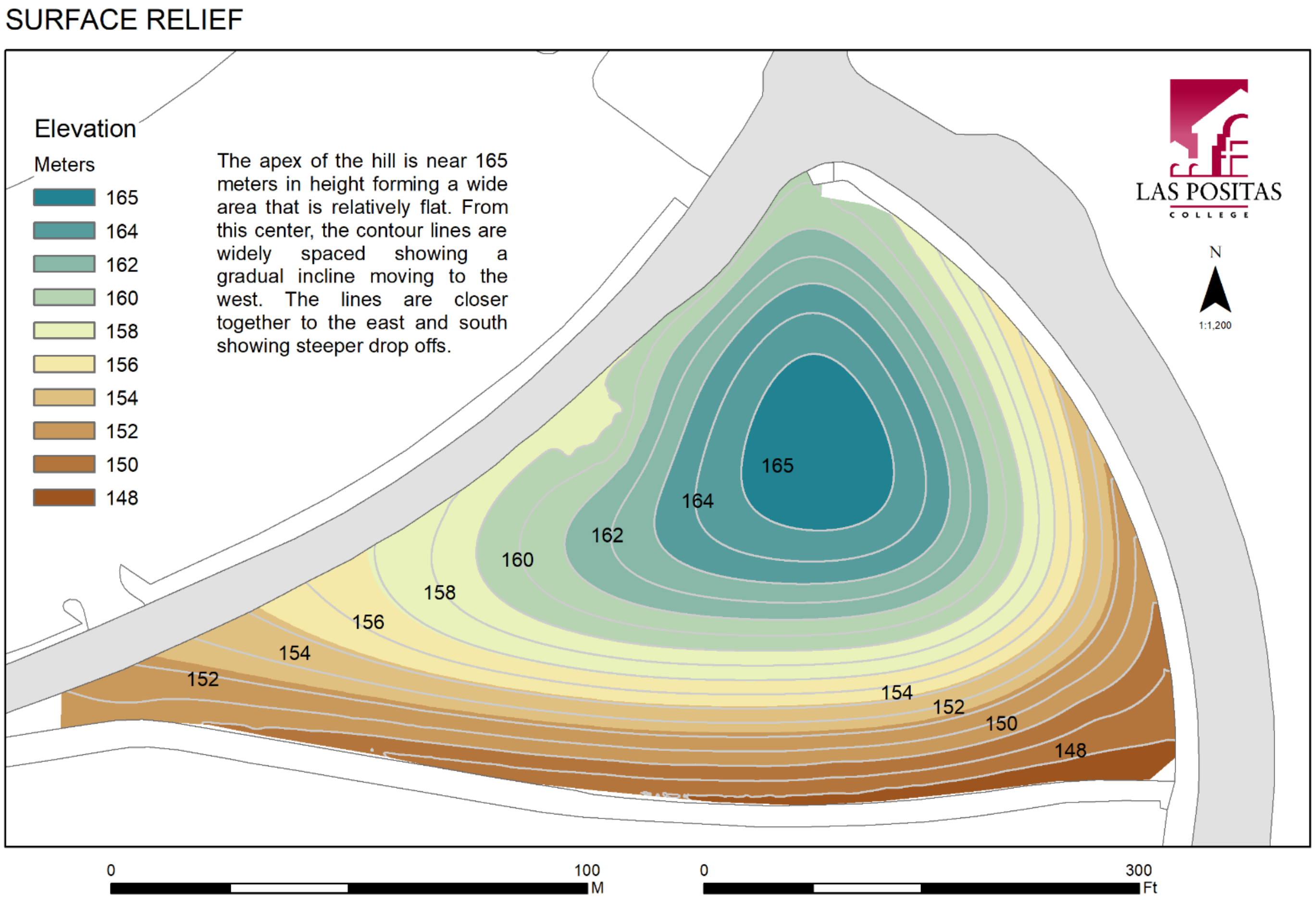
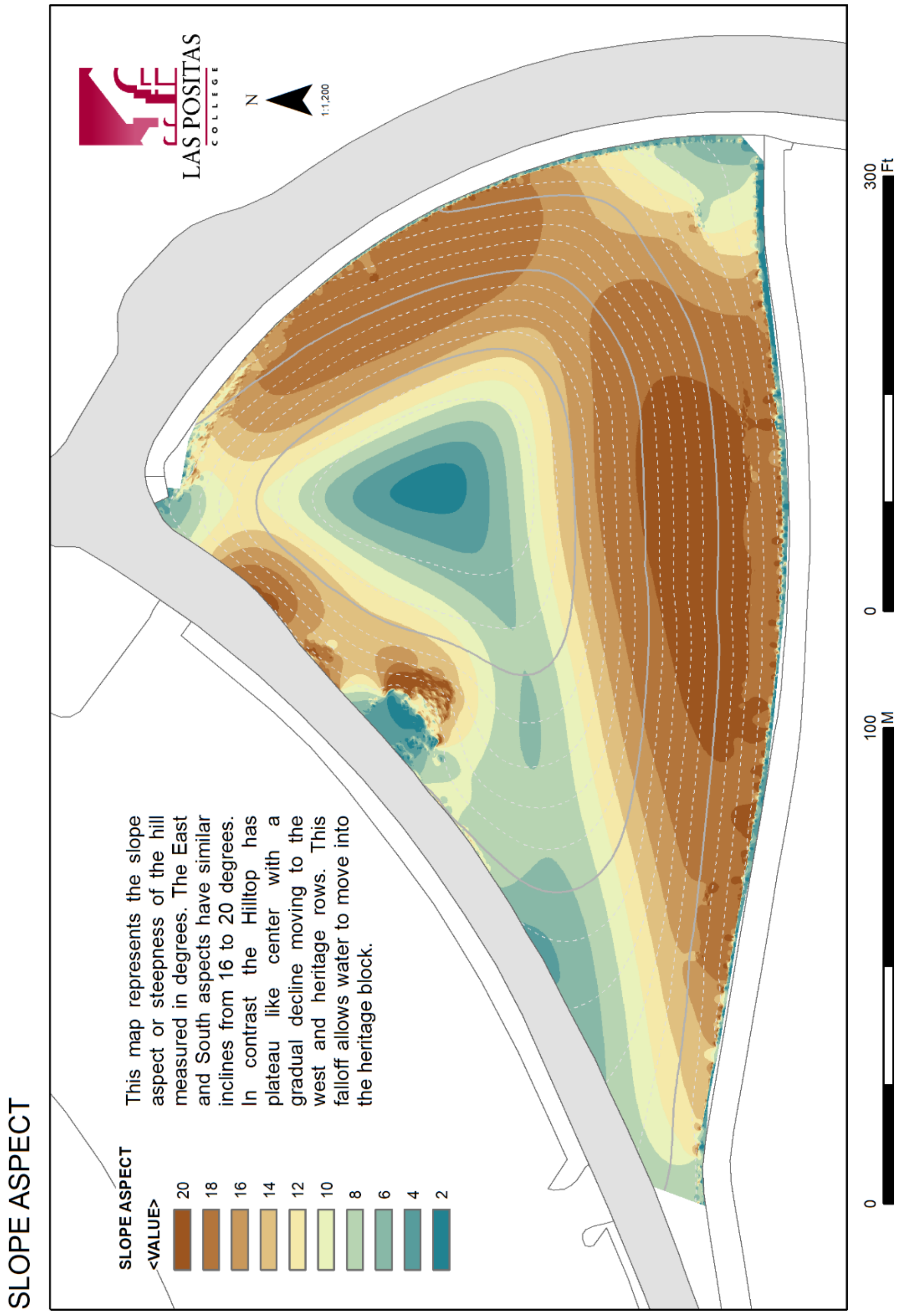


Figure 13 - DSM Cross section of vineyard with vegetation intact.



The apex of the hill is near 165 meters in height forming a wide area that is relatively flat. From this center, the contour lines are widely spaced showing a gradual incline moving to the west. The lines are closer together to the east and south showing steeper drop offs.

Figure 14 - Contour map



SLOPE ASPECT

This map represents the slope aspect or steepness of the hill measured in degrees. The East and South aspects have similar inclines from 16 to 20 degrees. In contrast the Hilltop has plateau like center with a gradual decline moving to the west and heritage rows. This falloff allows water to move into the heritage block.

Figure 15 - Slope aspect

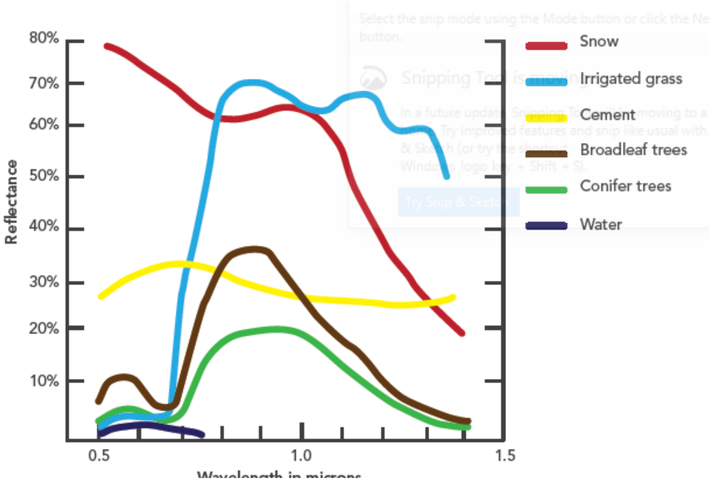


Figure 17 - Comparison of reflectance across different features (ESRI)

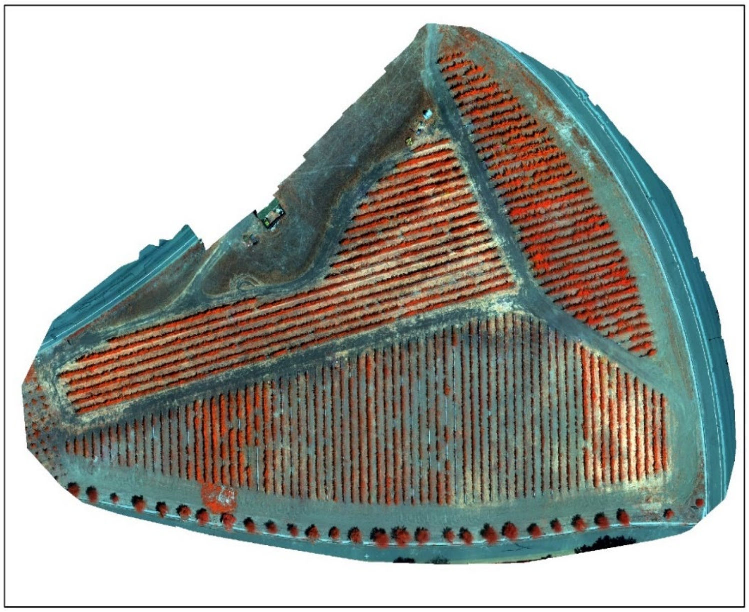
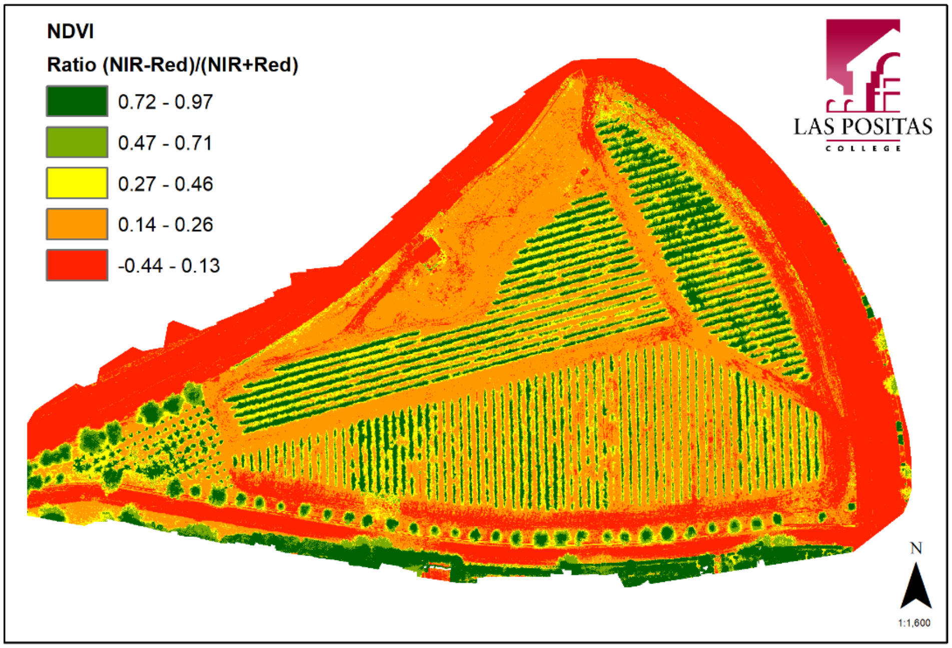
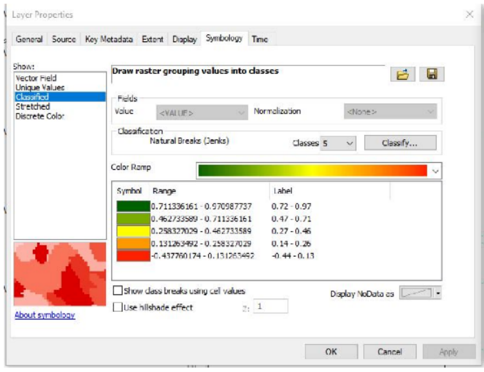


Figure 16 - Color InfraRed (CIR)Composite

Normalized Difference Vegetation Index (NDVI)





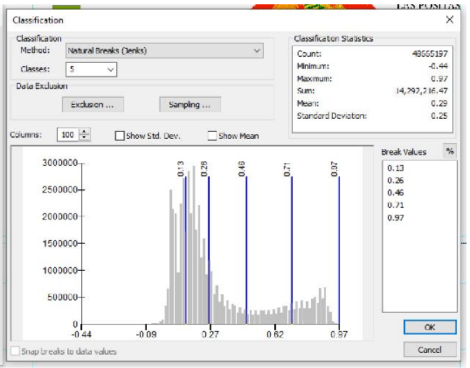
Draw raster grouping values into classes

Fields
Value: <VALUE>
Normalization: <None>

Classification
Natural Breaks (Jenks)
Classes: 5
Classify...

Symbol	Range	Label
🟩	0.711336161 - 0.970987737	0.72 - 0.97
🟩	0.462733589 - 0.711336161	0.47 - 0.71
🟨	0.258327029 - 0.462733589	0.27 - 0.46
🟧	0.131263492 - 0.258327029	0.14 - 0.26
🟥	-0.437760174 - 0.131263492	-0.44 - 0.13

☐ Show class breaks using cell values
☐ Use hillshade effect Z: 1
Display NoData as



Classification
Method: Natural Breaks (Jenks)
Classes: 5
Data Exclusion

Classification Statistics

Count:	48665197
Minimum:	-0.44
Maximum:	0.97
Sum:	14,292,216.47
Mean:	0.29
Standard Deviation:	0.25

Columns: 100 ☐ Show Std. Dev. ☐ Show Mean

Break Values
0.13
0.26
0.46
0.71
0.97

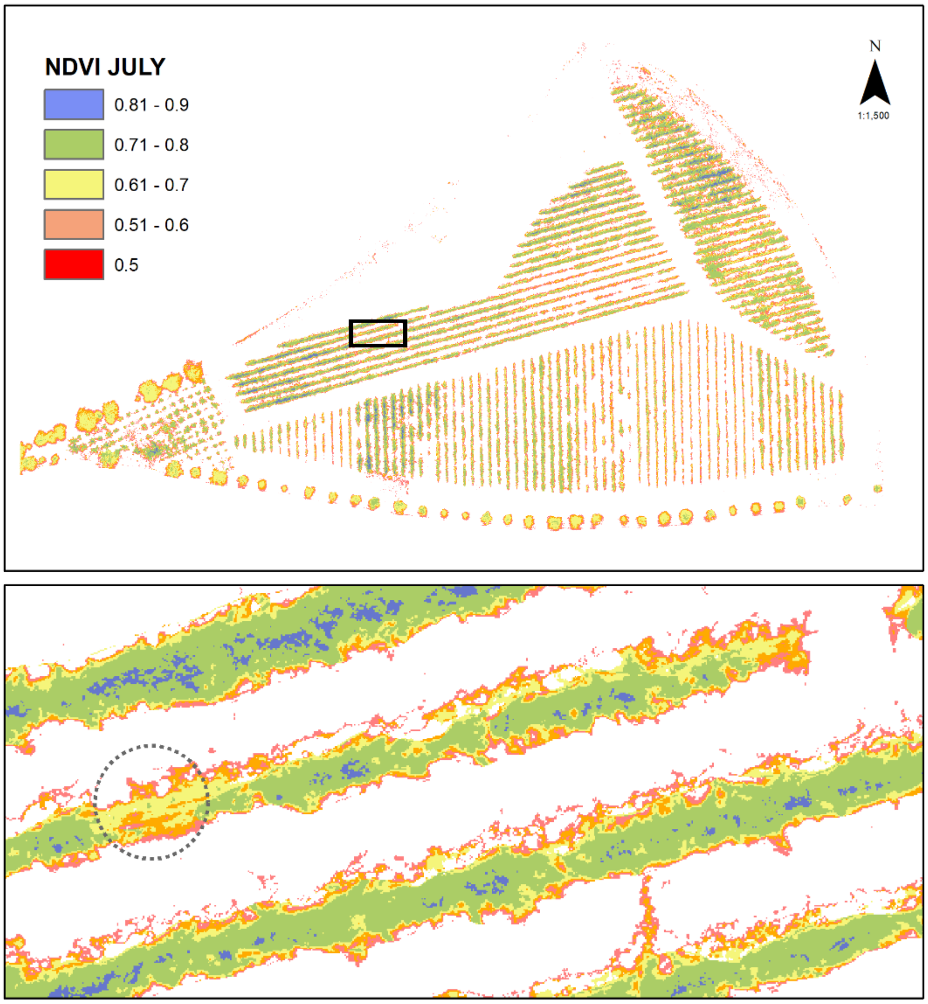
☐ Snap breaks to data values

This index is created as a ration between the Red and Near InfraRed bands. The result emphasizes how non-visible light is absorbed and reflected by different natural elements. For example, in this image the vegetation is highly reflective (green-yellow) since plants tend to absorb visible light. In contrast, soils, concrete, and asphalt (red-orange) are mildly reflective and absorb some of the non-visible light. This phenomenon allows us to clearly identify certain natural features, including shadows created in the capturing of data.

The lower image to the left reflects the color indexing which is manipulated to highlight certain features over others. The lower right-hand image is the histogram which allows us to aggregate the data, in this case it is done by "natural breaks" or where the data tends to be more often grouped.

Figure 18 - NDVI index of entire survey area

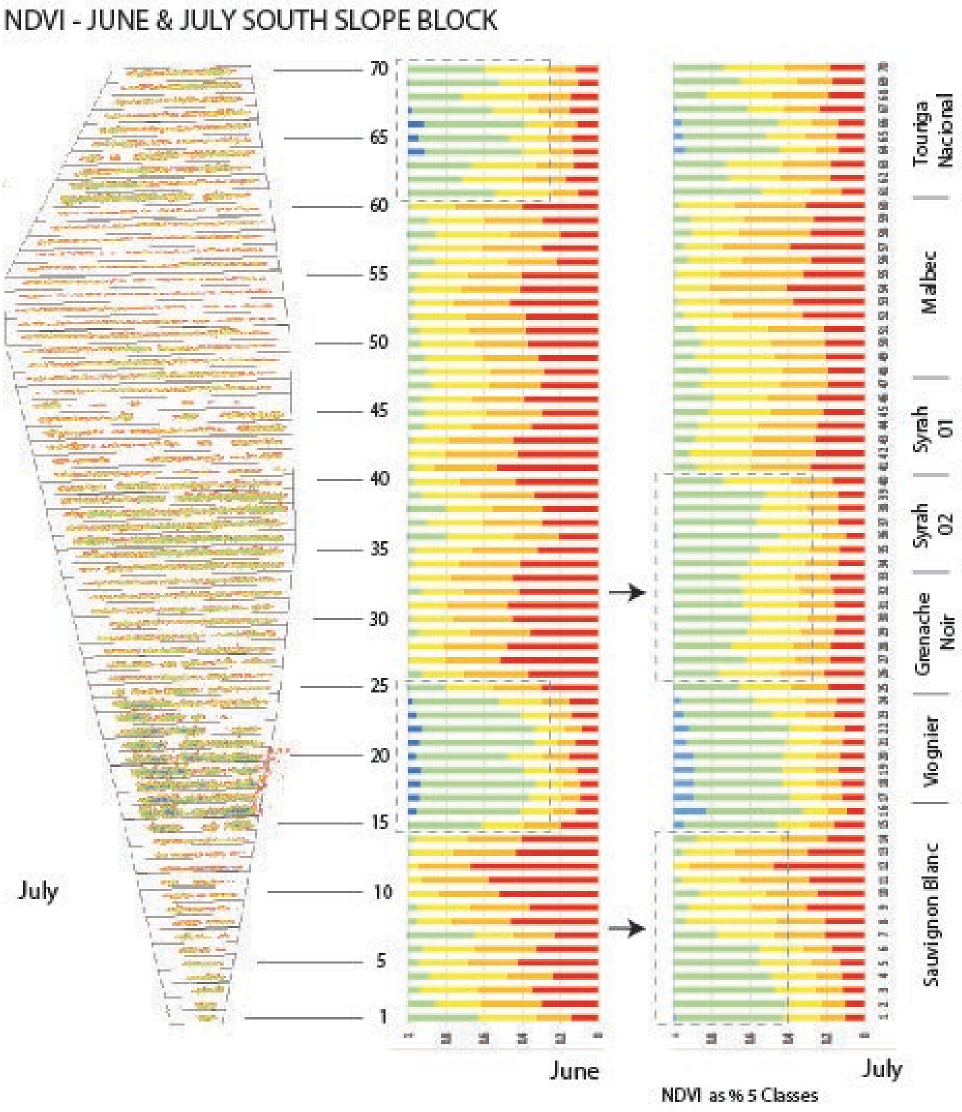
NDVI - Cultivated Area Isolated



The top image is the NDVI index of the cultivated area and categorized in 5 groupings. The higher values represent high reflectance versus low reflectance. In broad terms the higher the values indicate healthier and more vigorous plants. The five groups of values reflectance are equally defined in .10 increments. In this image certain parts of the vineyard have higher concentrations of higher values (blue and green) while others tend to be less dense and more lower values (red and orange).

The lower image focuses on a single area to show the variation present among rows. By visually comparing the distribution of values certain patterns can emerge. For example, the dashed line circle shows an area of interest, these can be followed up by field observations to verify potential cause for the variation: natural growth variation, thinning, irrigation, disease, pests, nutrition, or unknown.

Figure 19 - NDVI Cultivated area isolated


NDVI - JUNE & JULY SOUTH SLOPE BLOCK

NDVI as % 5 Classes

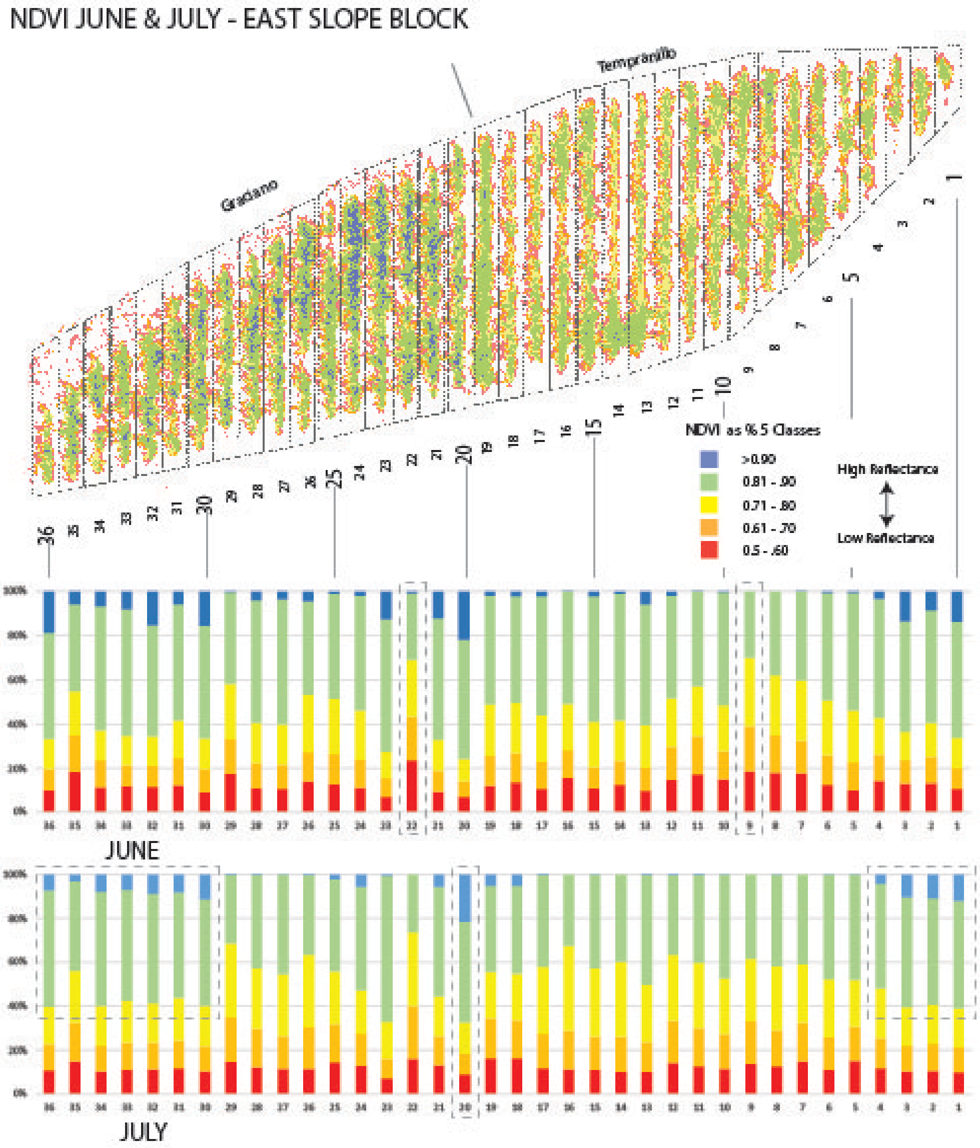
- 🟦 >0.90
- 🟩 0.81 - .90
- 🟨 0.71 - .80
- 🟧 0.61 - .70
- 🟥 0.5 - .60

High Reflectance ↕ Low Reflectance

Above is the five values of the NDVI classes generated as a defined interval of 0.1 for June and July. The higher values in blue and green show high reflectance which is associated with healthy vegetation. In contrast the low reflectance in red and orange are associated with lower levels of chlorophyll production.

The graph shows well performing area in rows 15 -25 and 61-70, the former can be linked to an overwatering event. In June, there were many rows, 1-14 and 26-60 which showed low values. In comparison to July a large portion of these, rows 1-14 and 26-40 seemed to strengthen in the mid values. It does seem that there was a reduction in low values over all from June to July. These row values can be further parsed and examined, for example row 12 seems to exhibit a signature unique to others and may be a candidate for a field observation. In general, this is a comparative method that is relative to its position and timing.

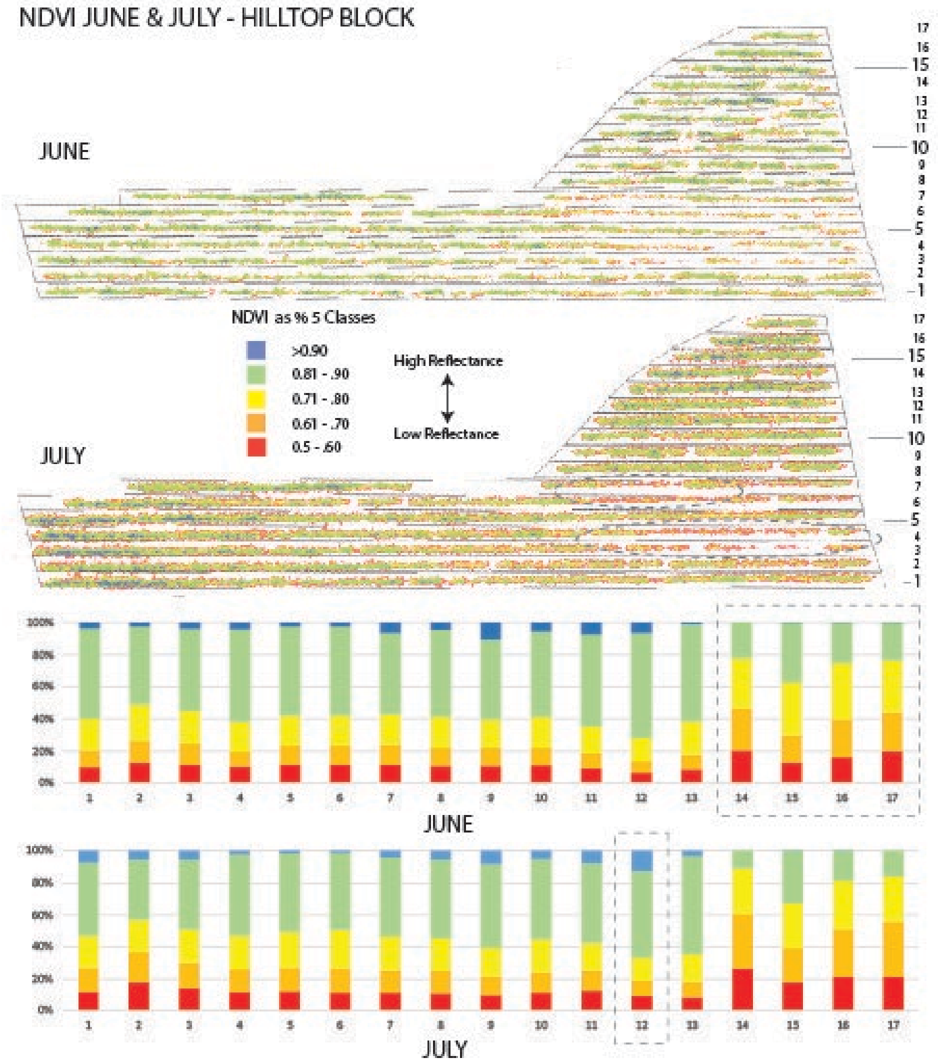
Figure 20 - NDVI - South Block interpretation



Above is the five values of the NDVI classes generated as a defined interval of 0.1 for June and July. The higher values in **blue** and **green** show high reflectance which is associated with healthy vegetation. In contrast the low reflectance in **red** and **orange** are associated with lower levels of chlorophyll production.

The two charts compare the June to July values for each row. In contrast to other areas of the vineyard, there seems to be little variation between observations. Instead, the East Slope Block seems to be on a relatively consistent growth trajectory. A few rows seem to have slightly higher values, 30-36 and 1-5 with row 20 expressing higher than most. Only two rows in June, 9 and 22, seemed to be outliers and exhibit a wider breadth of low and mid-range values.

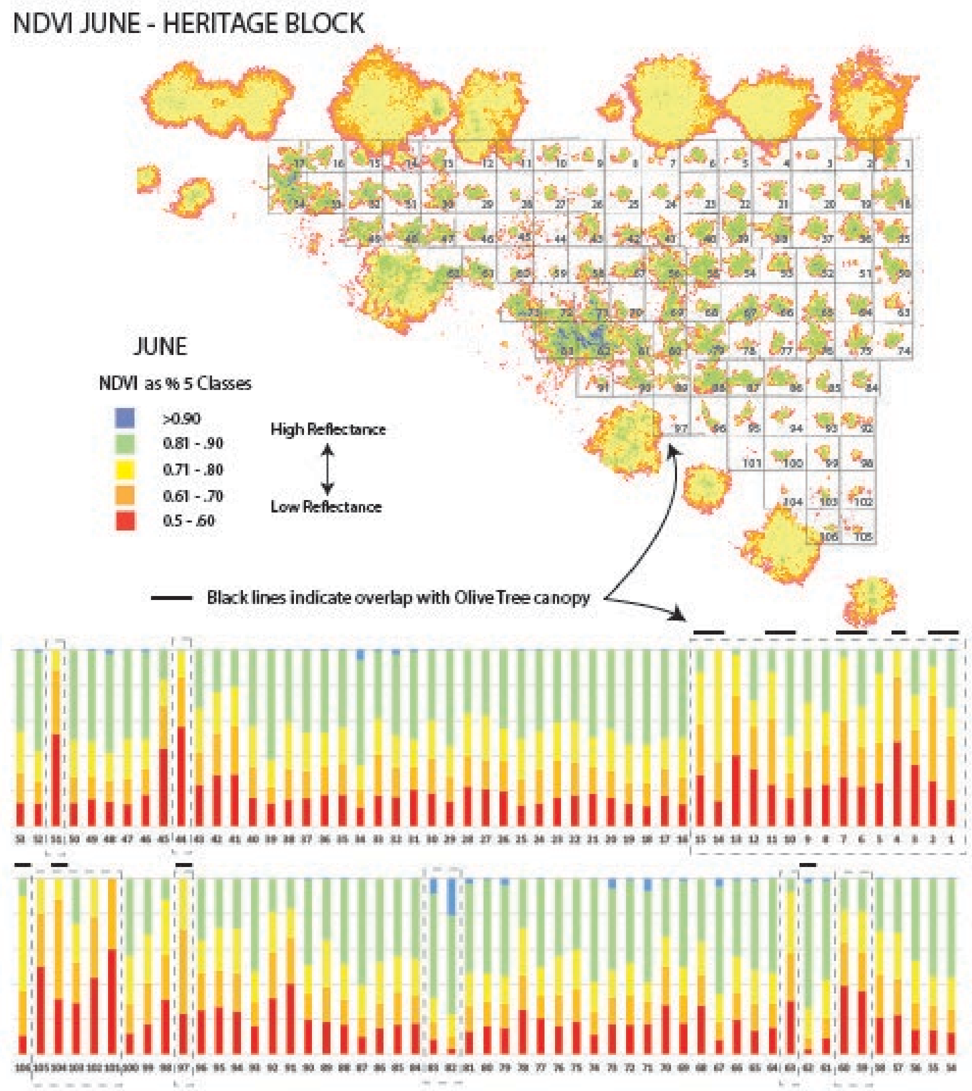
Figure 21 - NDVI - East Block interpretation



Above is the five values of the NDVI classes generated as a defined interval of 0.1 for June and July. The higher values in blue and green show high reflectance which is associated with healthy vegetation. In contrast the low reflectance in red and orange are associated with lower levels of chlorophyll production.

There seems to be little variation between observations, however two areas may be highlighted. The first are rows 14-17 which seem to have a more dispersed representation of the mid to low values in comparison to the entire block. In contrast, row 12 seems to be the more vibrant and vigorous of the block. Apart from the aggregate values, the image shows visible thinning and low values in rows 3-4 and 6-7 located in the western area. These are highlighted with grey oval dashed lines.

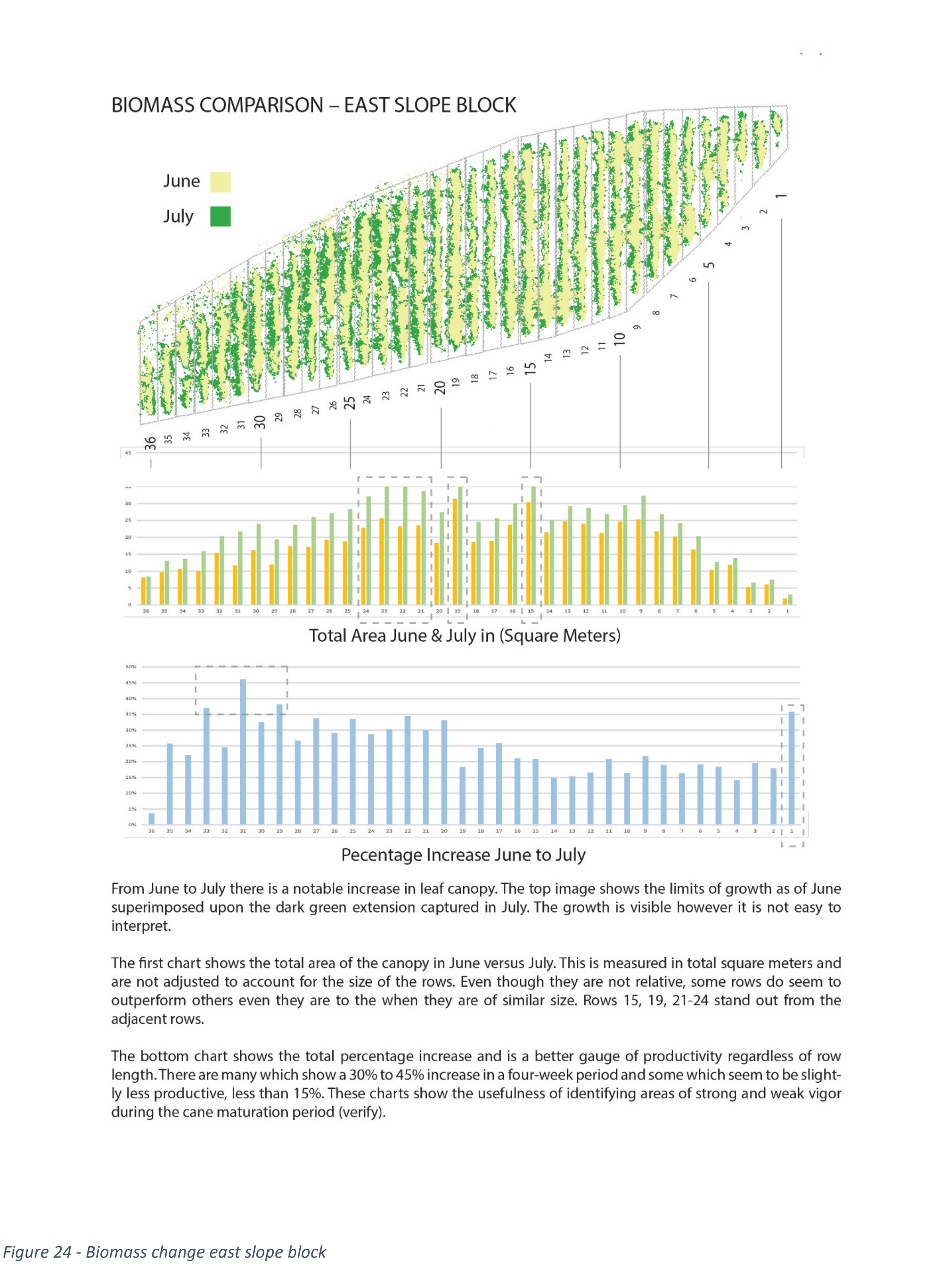
Figure 22 - NDVI – Hilltop Block interpretation



Above is the five values of the NDVI classes generated as a defined interval of 0.1 for July. The higher values in blue and green show high reflectance which is associated with healthy vegetation. In contrast the low reflectance in red and orange are associated with lower levels of chlorophyll production.

The above chart are the reflectance values for each individual vine as opposed to an aggregate of a row. This allows us to focus on the wellbeing of a singular vine. Overall, there is considerable variation among observations. Some of this is caused by the proximity and overlap of adjacent olive trees, however much of it the difference occurs within the rows. The chart can easily identify specific vines which exhibit extremely limited growth, 44, 51, 97 and 101. Other groups of vines seem to have values that contrast, 82 and 83 have large canopies and vigor, while 101-105 seem to be or smaller size and lower values.

Figure 23 - NDVI Heritage Block interpretation



BIOMASS COMPARISON – EAST SLOPE BLOCK

Total Area June & July in (Square Meters)

Pecentage Increase June to July

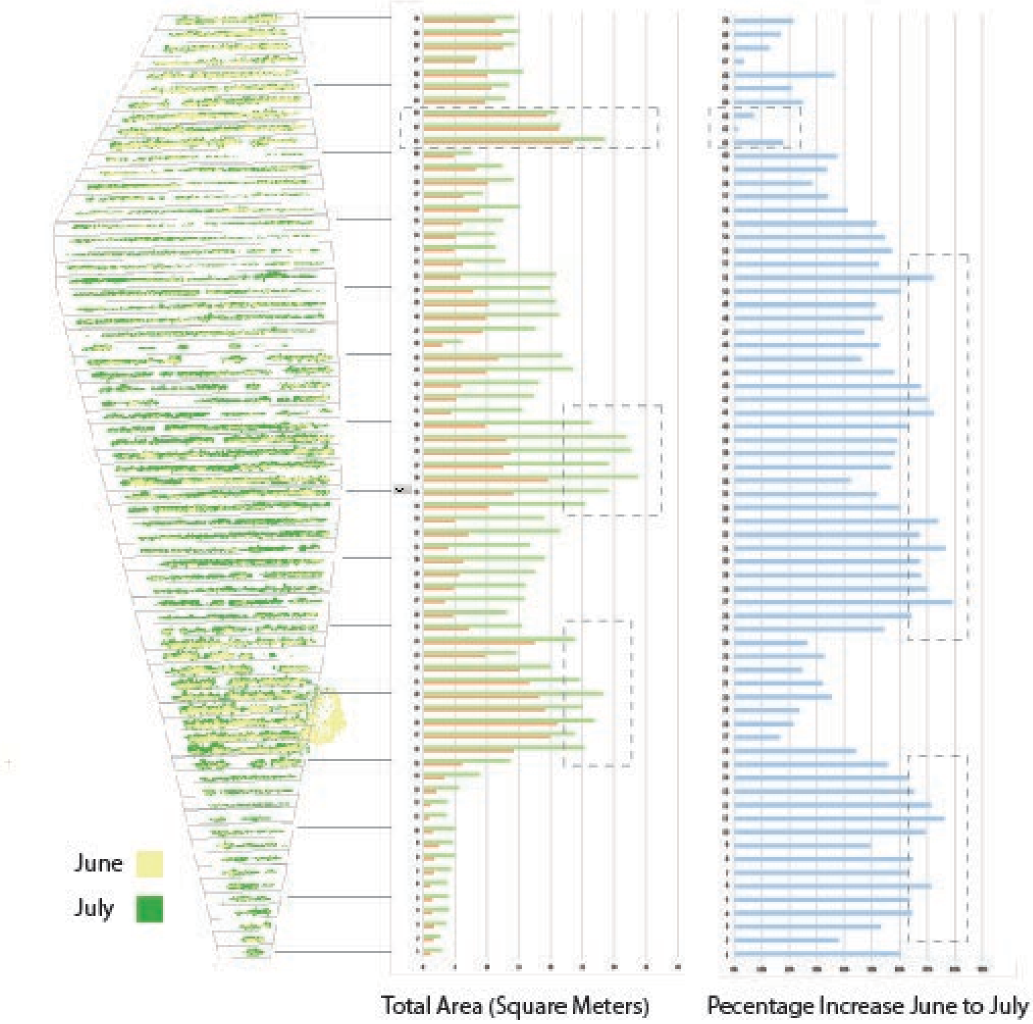
From June to July there is a notable increase in leaf canopy. The top image shows the limits of growth as of June superimposed upon the dark green extension captured in July. The growth is visible however it is not easy to interpret.

The first chart shows the total area of the canopy in June versus July. This is measured in total square meters and are not adjusted to account for the size of the rows. Even though they are not relative, some rows do seem to outperform others even they are to the when they are of similar size. Rows 15, 19, 21-24 stand out from the adjacent rows.

The bottom chart shows the total percentage increase and is a better gauge of productivity regardless of row length. There are many which show a 30% to 45% increase in a four-week period and some which seem to be slightly less productive, less than 15%. These charts show the usefulness of identifying areas of strong and weak vigor during the cane maturation period (verify).

Figure 24 - Biomass change east slope block

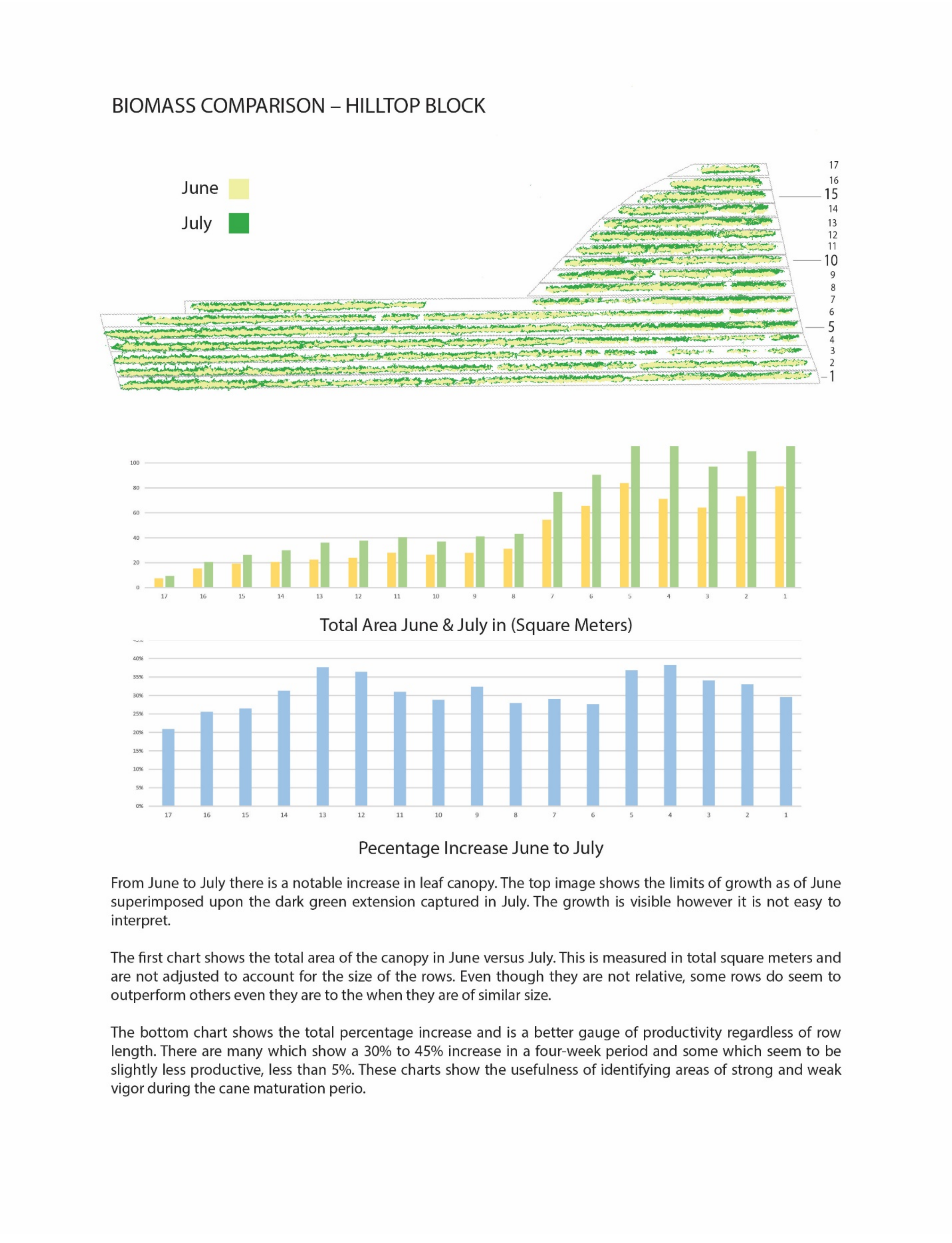
BIOMASS COMPARISON – SOUTH SLOPE BLOCK



From June to July there is a notable increase in leaf canopy. The left image shows the limits of growth as of June superimposed upon the dark green extension captured in July. The growth is visible however it is not easy to interpret. The first chart shows the total area of the canopy in June versus July. This is measured in total square meters and are not adjusted to account for the size of the rows. Even though they are not relative, some rows do seem to outperform others even they are to the when they are of similar size. Rows 16-24, 34-40, and 61-63 stand out from the adjacent rows.

The left chart shows the total percentage increase and is a better gauge of productivity regardless of row length. There are many which show a 60% increase in a four-week period and some which seem to be slightly less productive, less than 15%. These charts show the usefulness of identifying areas of strong and weak vigor during the cane maturation period (verify).

Figure 25 - Biomass change south slope block



BIOMASS COMPARISON – HILLTOP BLOCK

Total Area June & July in (Square Meters)

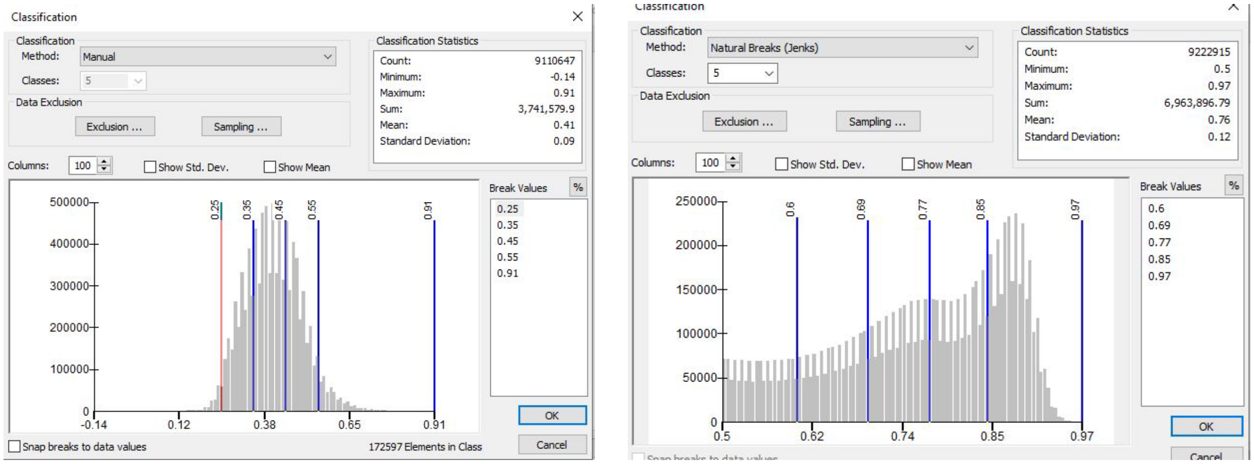
Pecentage Increase June to July

From June to July there is a notable increase in leaf canopy. The top image shows the limits of growth as of June superimposed upon the dark green extension captured in July. The growth is visible however it is not easy to interpret.

The first chart shows the total area of the canopy in June versus July. This is measured in total square meters and are not adjusted to account for the size of the rows. Even though they are not relative, some rows do seem to outperform others even they are to the when they are of similar size.

The bottom chart shows the total percentage increase and is a better gauge of productivity regardless of row length. There are many which show a 30% to 45% increase in a four-week period and some which seem to be slightly less productive, less than 5%. These charts show the usefulness of identifying areas of strong and weak vigor during the cane maturation perio.

Figure 26 - Biomass change hilltop block



Classification

Classification
Method: Manual
Classes: 5

Data Exclusion

Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Classification Statistics
Count: 9110647
Minimum: -0.14
Maximum: 0.91
Sum: 3,741,579.9
Mean: 0.41
Standard Deviation: 0.09

Break Values
0.25
0.35
0.45
0.55
0.91

☐ Snap breaks to data values
172597 Elements in Class

Classification

Classification
Method: Natural Breaks (Jenks)
Classes: 5

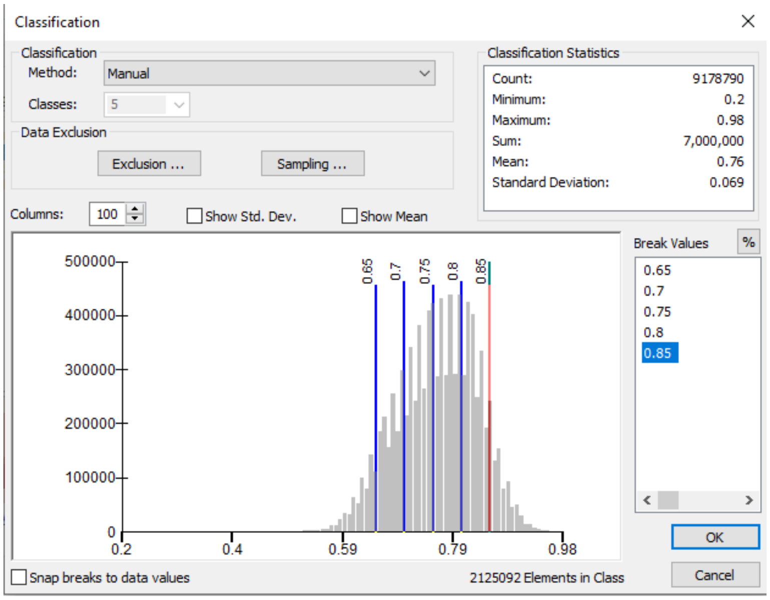
Data Exclusion

Columns: 100
☐ Show Std. Dev.
☐ Show Mean

Classification Statistics
Count: 9222915
Minimum: 0.5
Maximum: 0.97
Sum: 6,963,896.79
Mean: 0.76
Standard Deviation: 0.12

Break Values
0.6
0.69
0.77
0.85
0.97

Figure 27 - NDVI/NDVE histogram comparison



Classification

Classification
Method: Manual
Classes: 5

Data Exclusion

Columns: 100
☐ Show Std. Dev.
☐ Show Mean

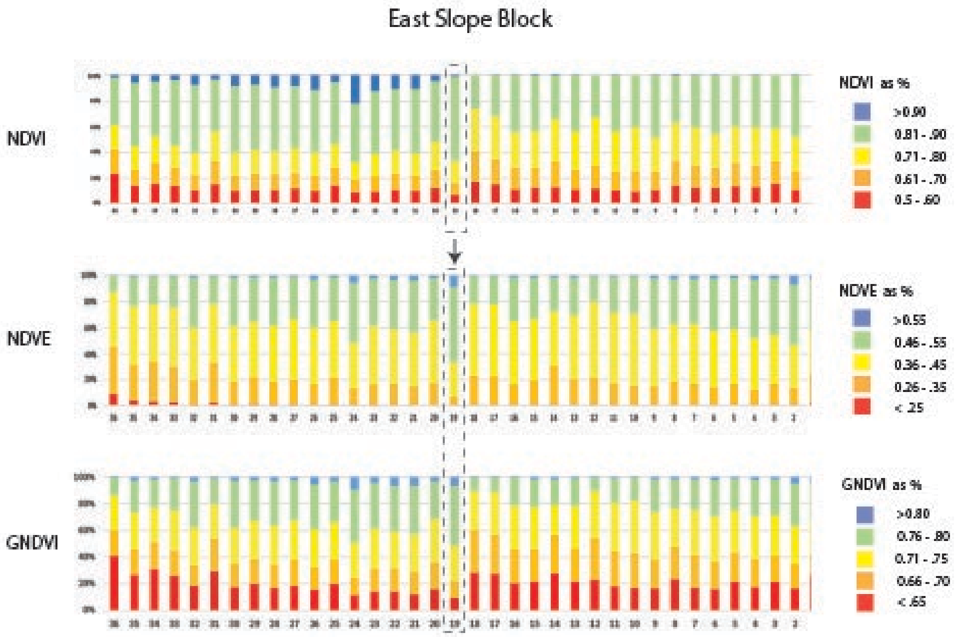
Classification Statistics
Count: 9178790
Minimum: 0.2
Maximum: 0.98
Sum: 7,000,000
Mean: 0.76
Standard Deviation: 0.069

Break Values
0.65
0.7
0.75
0.8
0.85

☐ Snap breaks to data values
2125092 Elements in Class

Figure 28 - GNDVI histogram

INDEX COMPARISION - EAST SLOPE BLOCK



The purpose of this comparison is to better understand the relationship between the three indexes and if NDVE and GNDVI might highlight certain areas that are not apparent in NDVI.

NDVE and GNDVI

There is a general symmetry of values between the two indexes. NDVE has less representation of the five classes, yet this may related to poor interval choice. Based upon the graphs, it seems that the block is experiencing relatively similar nitrogen uptake and relative even moisture retention.

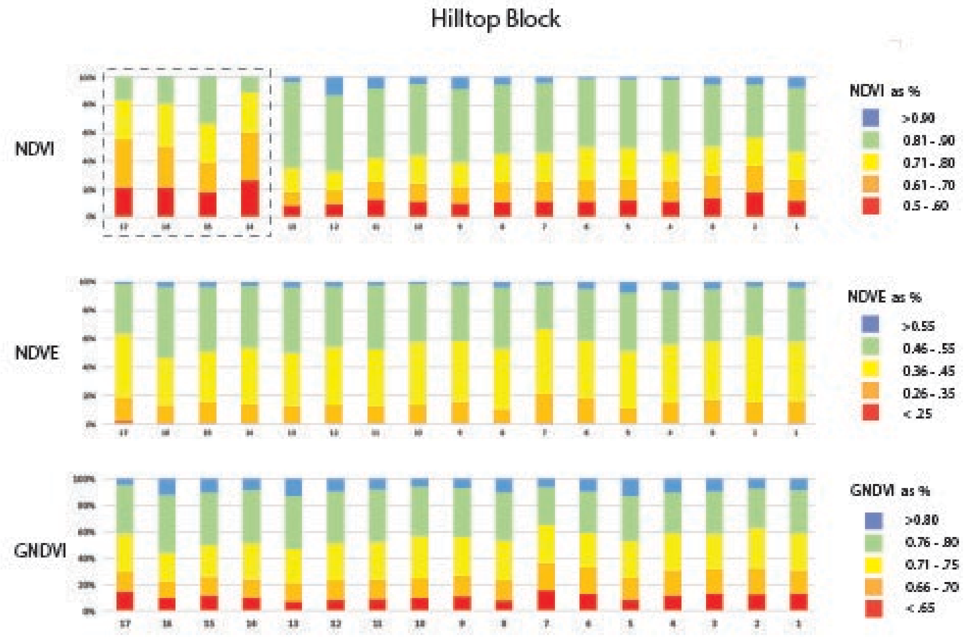
NDVI vs. NDVE/GNDVI

The midrange values for each index tend to align, as highlighted in row 19.

- **NDVI** is the most common agricultural index for general plant health productionand is associated with chlorophyll production
- **NDVE** uses the non-visible spectrum exclusively, which can identify areas of low chlorophyll content, indicating nitrogen limitation in the leaves, making it a sensitive index for monitoring chlorophyll content (Boiarskii et. All 2019).
- **GNDVI** has been observed to show nitrogen retention and relative moisture. Since these two indexes are focused on two different light combinations, the values themselves are less important than their distribution between low to high.

Figure 29 - Index comparison East Slope Block

INDEX COMPARISION - HILLTOP BLOCK



The purpose of this comparison is to better understand the relationship between the three indexes and if NDVE and GNDVI might highlight certain areas that are not apparent in NDVI.

NDVE and GNDVI

There is a general symmetry of values between the two indexes. NDVE has less variation in the five Classes, yet this may related to poor interval choice. Based upon the graphs, it seems that the block is experiencing relatively similar nitrogen uptake and relative even moisture retention.

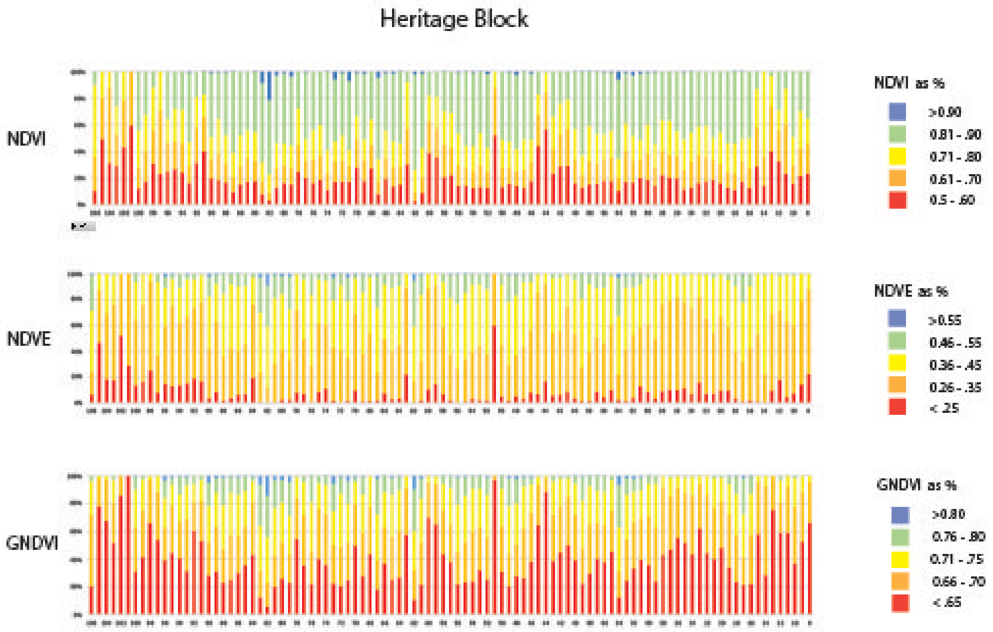
NDVI vs. NDVE/GNDVI

The midrange values for each index tend to align, however rows 17-14 in NDVI deviate in patterning from the other two indexes. The NDVI is showing a wider range of lower values than adjacent rows. This may indicate that the NDVI values show some form of plant stress unrelated to moisture or nitrogen?

- **NDVI** is the most common agricultural index for general plant health productionand is associated with chlorophyll production
- **NDVE** uses the non-visible spectrum exclusively, which can identify areas of low chlorophyll content, indicating nitrogen limitation in the leaves, making it a sensitive index for monitoring chlorophyll content (Boiarskii et. All 2019).
- **GNDVI** has been observed to show nitrogen retention and relative moisture. Since these two indexes are focused on two different light combinations, the values themselves are less important than their distribution between low to high.

Figure 30 - Index comparison Hilltop Block

INDEX COMPARISION - HERITAGE SLOPE BLOCK



The purpose of this comparison is to better understand the relationship between the three indexes and if NDVE and GNDVI might highlight certain areas that are not apparent in NDVI.

NDVE and GNDVI

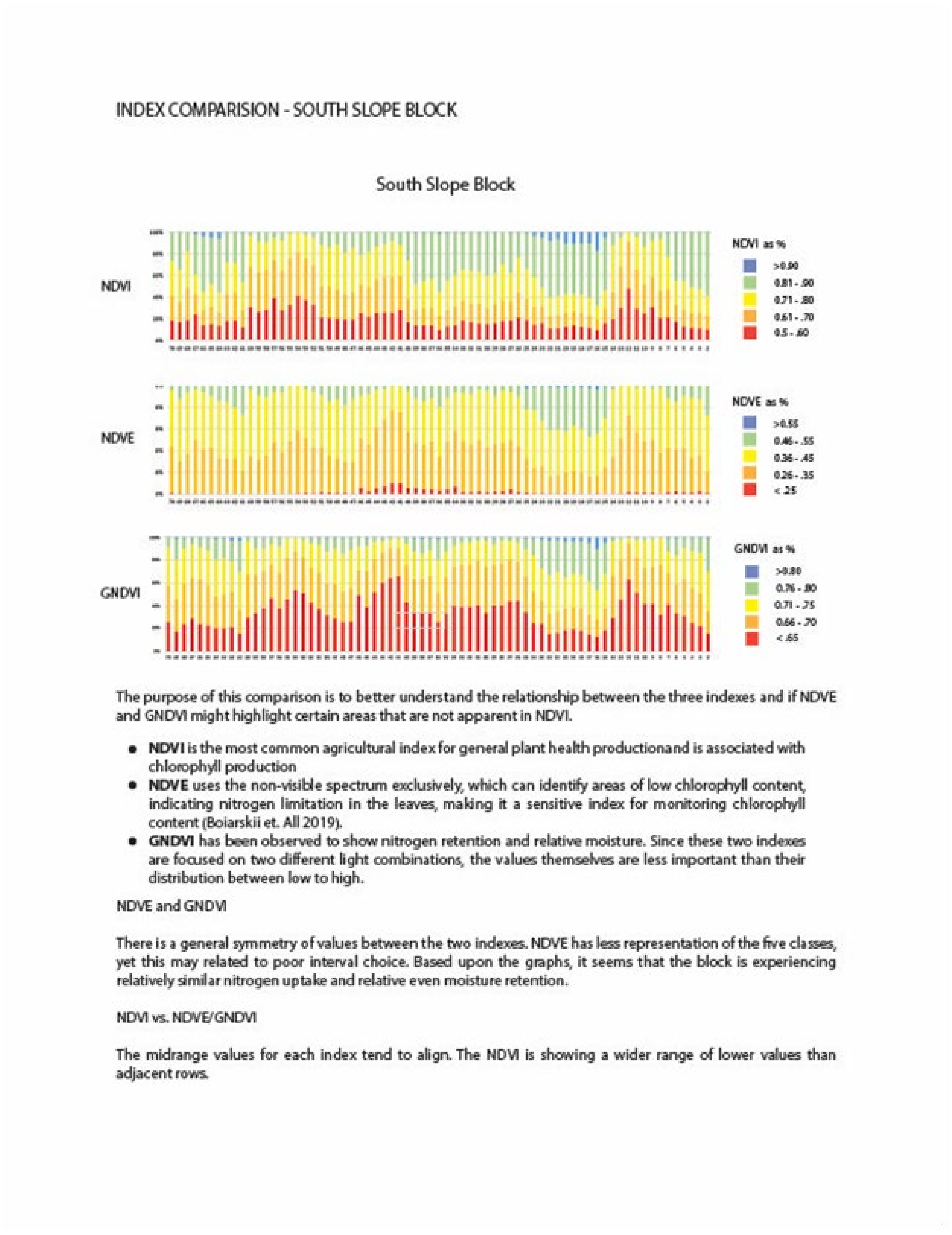
There is a general symmetry of values between the two indexes. NDVE has less representation of the five classes, yet this may related to poor interval choice. Based upon the graphs, it seems that the block is experiencing relatively similar nitrogen uptake and relative even moisture retention.

NDVI vs. NDVE/GNDVI

The heritage block is dry farmed and may be an area where GNDVI may become very useful.

- **NDVI** is the most common agricultural index for general plant health productionand is associated with chlorophyll production
- **NDVE** uses the non-visible spectrum exclusively, which can identify areas of low chlorophyll content, indicating nitrogen limitation in the leaves, making it a sensitive index for monitoring chlorophyll content (Boiarskii et. All 2019).
- **GNDVI** has been observed to show nitrogen retention and relative moisture. Since these two indexes are focused on two different light combinations, the values themselves are less important than their distribution between low to high.

Figure 31 - Index comparison South Slope Block



INDEX COMPARISION - SOUTH SLOPE BLOCK

The purpose of this comparison is to better understand the relationship between the three indexes and if NDVE and GNDVI might highlight certain areas that are not apparent in NDVI.

- **NDVI** is the most common agricultural index for general plant health productionand is associated with chlorophyll production
- **NDVE** uses the non-visible spectrum exclusively, which can identify areas of low chlorophyll content, indicating nitrogen limitation in the leaves, making it a sensitive index for monitoring chlorophyll content (Boiarskii et. All 2019).
- **GNDVI** has been observed to show nitrogen retention and relative moisture. Since these two indexes are focused on two different light combinations, the values themselves are less important than their distribution between low to high.

NDVE and GNDVI

There is a general symmetry of values between the two indexes. NDVE has less representation of the five classes, yet this may related to poor interval choice. Based upon the graphs, it seems that the block is experiencing relatively similar nitrogen uptake and relative even moisture retention.

NDVI vs. NDVE/GNDVI

The midrange values for each index tend to align. The NDVI is showing a wider range of lower values than adjacent rows.

Figure 1 - Index comparison Heritage Block

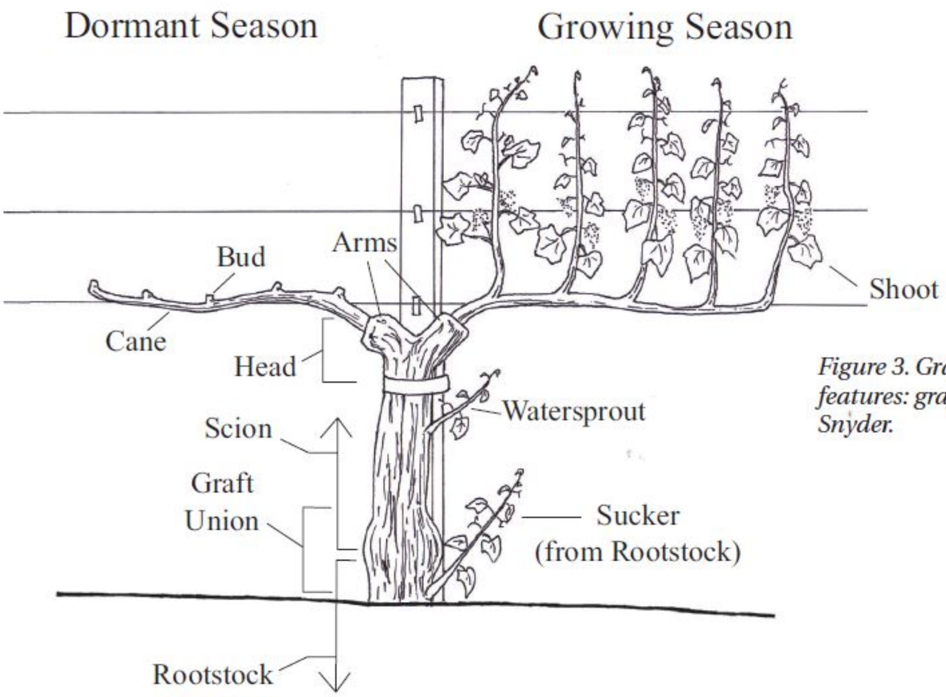


Figure 3. Grapevine structures and features: grafted vine. Drawing by Scott Snyder.

Figure 33 - Grapevine structure (Hellman 2013)

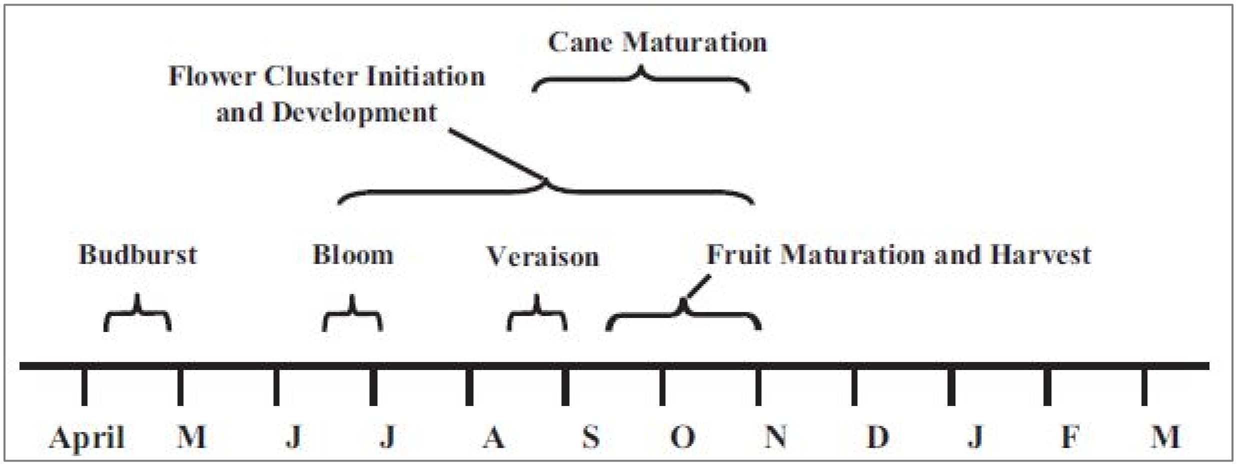


Figure 33 - Annual cycle of grapevine growth (Hellman 2013)