ECOSYSTEM-CONDITION EVALUATION OF THE COMPLEX, CRITICALLY-ENDANGERED PINE ROCKLAND ECOSYSTEM: INDICATORS, UNMANNED AERIAL SYSTEMS (UAS), AND AN EMPHASIS ON HERBACEOUS GROUND COVER DIVERSITY

by

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Ecosystem-Condition Evaluation of the Complex, Critically-Endangered Pine Rockland Ecosystem: Indicators, Unmanned Aerial Systems (UAS), and an Emphasis on Herbaceous Ground Cover Diversity

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LIST OF ABBREVIATIONS

Complex Adaptive System .... CAS
Department of Interior .... DOI
Digital Surface Model .... DSM
Federal Aviation Administration .... FAA
Fire Return Interval .... FRI
Low Altitude Quadrat Imagery .... LAQI
Miami-Dade .... M-D
Multispectral .... m-s
Near-Infrared .... NIR
Normalized Difference Vegetation Index .... NDVI
Orange-Cyan-Near Infrared .... OCN
Pilot in Command .... PIC
Pine Rockland .... PR
Primary Investigator .... PI
Project Aviation Safety Plan .... PASP
Red-Green-Blue .... RGB
Seasonally Dry Tropical Forests .... SDTF
South Florida .... S FL
System Evaluation Workbook .... SEW
Takeoff .... TO
Tropical Grassland Biome .... TGB
True-color .... t-c
Unmanned Aircraft Systems .... UAS
United States Fish and Wildlife Service .... USFWS
very High-Resolution .... vHR
Visible Atmospherically Resistant Index .... VARI
Visual Observer .... VO
Waypoint .... WPT

ABSTRACT

ECOSYSTEM-CONDITION EVALUATION OF THE COMPLEX, CRITICALLY-ENDANGERED PINE ROCKLAND ECOSYSTEM: INDICATORS, UNMANNED AERIAL SYSTEMS (UAS), AND AN EMPHASIS ON HERBACEOUS GROUND COVER DIVERSITY

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An ecosystem evaluation process was applied to the critically-endangered South Florida (S FL) pine rockland (PR)(pine/grassland) ecosystem, using a) unmanned aircraft systems (UAS) surveys, and newly-developed (under-the-canopy) UAS manual flight methods; b) the synthesis of multiple data sources and types; and c) the use of complex adaptive system (CAS) principles (redundancy, feedback loops, resiliency, alternative stable states), to identify healthy system indicators and evaluate system complexity and diversity; with the purpose of developing systematic ecosystem evaluation and reporting methods that can contribute to the advancement of ecosystem protection regulations, and the health assessment and conservation of global ecosystem biodiversity.

INTRODUCTION

Ecosystems are their own complex and diverse entities. Their health is directly related to global biodiversity, yet many of the world's ecosystems are degraded and endangered. Often ecosystems are evaluated from the perspective of individual species protection. An ecosystem evaluation process is meant to shift the scale of evaluation and the conservation-emphasis from the single-species focus to the ecosystem level in a comprehensive manner (Parrott and Meyer 2012). This research considered the complexity and interactions of a natural system using indicators to measure and characterize ecosystem condition. The incorporation of multiple data sources and types, including remote imagery, is utilized in the ecosystem evaluation process.

The Endangered Species Act and Habitat

Under the United States Endangered Species Act (ESA), species listing determinations (Endangered, Threatened, Not Warranted for listing) are assessed according to a set of five factors (Sec. 4 (a) (1), factors A-D[1]) most commonly executed through a species review and threats analysis. Factor A ("the present or threatened

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[1] Factors (A) the present or threatened destruction, modification, or curtailment of its habitat or range; (B) overutilization for commercial, recreational, scientific, or educational purposes; (C) disease or predation; ((D) the inadequacy of existing regulatory mechanisms; or (E) other natural or manmade factors affecting its continued existence (Sect. 4(a)(1).

destruction, modification, or curtailment of its habitat or range") specifically involves assessing threats to the species based on its habitat.

Habitat threats identified under Factor A are the most commonly identified threats, and often the primary threats, for determining that species warrant listing under the ESA. Habitat fragmentation can influence the distribution of rare plants, more than climate or edaphic (soil-related) conditions (McCune 2016); this may be especially true in urban systems. Also, multiple species occurring within the same defined habitat are being listed concurrently with "habitat loss, modification, and curtailment of habitat or range" identified as the leading threats for the need to list these species. Examples include the ESA listing of four Everglades plants (United States Fish and Wildlife Service [USFWS] 2017 [82 FR 46691]), four Florida Keys plants (USFWS 2016 [81 FR 66842]), two Pine Rockland (PR) plants (USFWS 2014a [79 FR 52567]), and two South Florida (S FL) cactus plants (USFWS 2013 [78 FR 63796]).

Multi-species recovery plans have been developed for addressing species recovery actions for suites of listed species co-occurring and experiencing similar habitat-related threats within specific ecological communities, however recovery strategies are generally still single-species based (USFWS 1999; NOAA 2020). Because the determination of an Endangered and Threatened status is species-based, the condition of the habitat or ecosystem is described in terms of how the stressors or threats act upon the species being reviewed. An ecosystem condition (loss or fragmentation, for example) is conveyed and analyzed as a threat *to* the species.

The challenge to provide resources and manpower using a recovery model currently based on single species-by-species recovery strategies becomes only more challenging and expensive as more species become vulnerable and need listing under the ESA, in large part due to habitat-scale related stressors (Schwartz 2008). The ESA (Section 2 (b)) states, "The purposes of this Act are to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved…." In language, the ESA recognizes the need to protect at the ecosystem level. It of course remains necessary to continue to examine the decline in ecosystem condition as a primary contributor to species vulnerability and loss. However, the species review and threats analysis process alone does not assure that ecosystems are being effectively assessed and protected under the ESA. Noss (2013. p. 137) succinctly communicated the issue, "…we have no Endangered Ecosystem Act, or similar law to protect them."

Endangered Ecosystems

Ecosystems are at risk on a global scale (Bland et al. 2017; Cardinale et al. 2012; Hooper et al. 2012; Tilman et al. 2014; Noss 1996; Noss et al. 1995). Many ecosystems including biodiversity hotspots have not been fully assessed, and climate-driven impacts such as sea level rise, increase risks to ecosystems, particularly to insular and coastal areas (Bellard et al. 2014). Future extinctions have been projected from climate driven-land use change (Jantz et al. 2015).

There is a need to assess the ecosystem as a whole, as its own entity, and to implement conservation and regulatory protective efforts at the ecosystem level. A framework can be developed to transition reviews beyond the often disparate single-species assessments, and enable efforts to target the root-causes of species endangerment and loss: ecosystem degradation and loss.

Ecosystems are CASs (Levin 1998; Parrott 2010; Odum 1988; Gunderson and Holling 2002). The complex factors and interactions that define CASs can be used to describe and assess ecosystem function and condition (Puettman et al. 2016; Norberg 2004; Parrott and Meyer, 2012; Pulla et al. 2015). Stated in Mouquet et al. (2013), "Landscapes are more than a simple collection of communities," but are a complex set of interacting globally-linked networks (Mouquet et al. 2013). Mouquet et al. (2013) presented a broader application of the keystone species concept indicating that ecosystems are themselves CASs, but they also exist and function within a complex, interconnected network of communities, or "metaecosystem." Some communities or ecosystems within a region, may similarly follow the concept of keystone species and play a role as a "keystone ecosystem" Mouquet et al. (2013). Wintle et al. (2019) supported the global synthesis of ecosystem information, and the valued contribution of even, small and fragmented habitats in global conservation.

In coordination with the IUCN global ecosystem risk assessment process, the initial definition and assessment of an ecosystem under review is produced by the assessors (Rodriguez et al. 2015; Bland et al. 2018; 2017). Instructions in the IUCN ecosystem risk assessment process state that assessors must select a variable to estimate environmental degradation, justify its suitability, and relate the variable to the capacity of the ecosystem to sustain its own identity (Rodriguez et al. 2015). Rowland et al. (2018), in identifying indicators for use in describing ecosystem risk, stated, “little guidance is available to select and use indicators for quantifying change at the ecosystem level to support risk assessments,” referring to the IUCN Ecosystem Risk Assessments (Bland et al. 2017; IUCN 2018; Rodriguez et al. 2015).

The identification and understanding of indicators that best constitute a “healthy” system is an effective component in land management decision-making and for helping to determine the likely return of investment on restoration efforts. Restoration of highly degraded habitat, or habitat that has crossed a threshold and moved into a novel condition (irreversible shift to an alternative state), may not provide a return on the restoration efforts (Hobbs et al. 2013; Herrick et al. 2019; Veldman et al. 2015; Rowland et al. 2018), and is a highly intensive exercise to attempt. Veldman et al. (2015) stated, “old-growth indicators species are very slow to re-establish. Grasslands on former agricultural lands are ecologically distinct from old growth.” It is generally more feasible to recover a system that possesses key intact indicators and function than to rebuild in an area that has shifted to a novel state.

The ability to infer ecological condition and measure system-level impacts is improved when there is an existing basis for comparison with a least-disturbed condition (Lopez and Frohn 2018; Pacheco et al. In: Aguirre and Sukuma 2017). The “historic” pre-human condition of a system may be unknown and no longer determinable. However, it is necessary to establish a baseline for use and reference to a set of indicators that represent a defined level of health based on good condition. This can be determined by using an integrative process; synthesizing various efforts and sources of knowledge and data. For example, inter-disciplinary information, such as data on the ancient limestone substrate of the Miami Ridge on which PR exits; archival, archaeological records on species use; and the UAS images of PR habitat acquired in this research, are used together to provide broader insight on the persistence of specific indicators and on habitat resilience (ability to withstand and recover from disturbance) than would a single data-source (Snyder 1990; Hoffmeister et al. 1967; Florida Museum 2020; University of Florida 2020). Seldom-considered system components may be used for evaluation. Pine canopy is an often-used indicator of pine forest habitat condition, however, other habitat components, such as the limestone substrate, or vegetative ground cover in a PR system, could be examined for their roles as indicators of system health.

Before assessing risk to an ecosystem, it is best to have an understanding of the intact system and identify indicators that reflect a healthy, functioning condition (van de Leemput et al. 2018; Schweiger et al. 2018; Keith 2015; Proulx 2007; Ghadami et al. 2018; Haase et al. 2018). Noss (2013) in his Preface wrote, "We need to know intimately that which we are trying to save, so that we can have some confidence that our conservation plans will meet the requirements for persistence of species and ecosystems." Bowman et al. (2015) and Herrick et al. (2019) described integrated methods for identifying reference conditions to measure landscape health and degradation, synthesizing various forms of information-gathering such as historical records and expert input.

Remotely-Sensed Imagery

While often an under-utilized source of information, remotely-sensed data is a highly valuable resource for ecosystem evaluations (Lausch et al. 2018; Zlinsky et al. 2015). The rapidly evolving unmanned aircraft systems (UAS) platforms and sensors provide very high-resolution (vHR) imagery, and with the readily-available image processing software, UASs are now regularly utilized in comprehensive ecosystem surveys and evaluations (Cruzan et al. 2016; Nagendra et al. 2012; Han et al. 2017). The small UAS platform (less than 25 kilograms [kg]; 55 pounds [lbs]) is an efficient tool for forestry and agricultural surveys, with the acquired images often used to classify canopy structure, or individual tree/crop cover or count (Dong et al. 2020; Zhang et al. 2016; Zahawi et al. 2015; Bagaram et al. 2018 and Getzin et al. 2012). Forest gap metrics (patches and space between trees at the canopy level), statistically derived from remotely-sensed imagery, have been commonly used to monitor or evaluate forest condition.

Using UAS imagery, Getzin et al. (2012) was one of the first studies to examine forest "understory diversity" by using forest canopy (gap) structure in a dense pine forest. Results by Getzin et al. (2012) found a strong relationship between disturbance patterns (open canopy gaps) and plant diversity. Available light, based on the canopy gap metric (shape, size, and distribution), was positively related to understory diversity but was not the only influencing factor. In addition, Getzin et al. (2012) noted the successful application of the UAS platform in this habitat study.

Bagaram et al. (2018) also tested the efficacy of using UAS-acquired, three-image band (3-band), Red Band 1-Green Band 2-Blue Band 3 (RGB) imagery, to calculate forest canopy patch metrics for assessing understory biodiversity features (understory density, development, and species richness) within a heavily-canopied, deciduous forest. Bagaram et al. (2018) found that the forest canopy patch metrics, using UAS RGB imagery, could be correlated to understory biodiversity features, and supported the integrated use of UASs and field data to map small forest areas.

Forest and agricultural surveys, and the use of the forest canopy structure or gap metrics to assess forest conditions, are a top-down analysis focusing on evaluating the condition of the system based on tree characteristics and gap patterns. Forest canopy gap patterns are one influence on understory biodiversity. However, UAS imagery acquired under the canopy and able to focus directly on the understory, or herbaceous ground cover (the suite of a variety of functioning forbs and grasses) of the open pine/grassland systems like PR, are lacking, and would provide unimpeded, detailed imagery for studying understory diversity.

Research Purpose

The purpose of this research was to develop systematic methods for an ecosystem evaluation of the critically endangered PR habitat, using site-scale UAS mapping and newly developed (under-the-canopy) survey methods for understanding the herbaceous ground cover diversity and health; and using existing available, efficient, and affordable resources such as imagery data, published works, local knowledge, and expert input. The evaluation is designed to complement global ecosystem conservation programs such as the IUCN Ecosystems Categories and Criteria process used to identify risk of ecosystem collapse (Bland et al. 2018; Keith 2015).

Research Questions

The objectives of this research are based on the following questions:

1. What is the most effective set of measurable biotic or abiotic indicators to evaluate the S FL PR system (including at least one functional group; and one spatial, and one temporal component)?
2. How will the UAS platform be best utilized to capture visual data on a) specific indictors or ecosystem conditions of characteristic PR habitat that include the ground cover mosaic (ground cover) (herbaceous; litter and fine soil; and exposed substrate limestone), solution holes, and pine forest, and b) varied PR ecosystem states (post-burn; wet-dry season) in select fire management units, and based on time since last burn, for use in assessing spectral signatures and structural components of vegetative condition?
3. What are the capabilities of UAS sensors in discriminating characteristic limestone substrate ground cover and hydrologic conditions of PR (within an (a) immediate- and (b) weeks- post-burn time interval)?
4. What survey protocols or combination of protocols will be most effective for collecting field verification data?
5. To what capacity can the necessary flight protocol and procedural safety plans for UAS surveys be developed into a comprehensive resource document for use in planning and implementing ecological surveys using UAS imagery?

LITERATURE REVIEW

In the process of researching and writing this dissertation, the author conducted a comprehensive literature search and review of published scientific literature; unpublished federal, state, and county reports; information obtained from informal interviews and questionnaires with local experts; and publicly available imagery resources.

The Ecosystem Concept and Biodiversity

Pickett and Cadenasso (2002) gives credit to Tansley (1935) for defining the term "ecosystem": a biotic community or assemblage and its physical environment in a specific place and which considers the interactions of its members. MacArthur (1955) indicated that community stability increased with the increase in the number of food web linkages, implying that species interactions and the strengths of interactions plays a role in stability as much as species populations. Patrick (1970) described ecosystem condition occurring as a function of the form of species representation and redundancy, and of both its biotic and abiotic processes. While focusing on species populations and abundance, early studies still indicated a conceptual understanding that a functioning system is defined by more than just a list of species or a defined boundary of habitat. Dasmann (1972) first classified natural regions by major faunal groups. Examples of current comprehensive ecosystem assessments include the Sage Prairie Ecosystem Assessment (species-based on sage grouse keystone species), and the IUCN Ecosystem Risk

Assessment process (risk-based) (Connelly et al. 2004; Bland et al. 2017). The sage-prairie ecosystem assessment while species centric, is a habitat-based framework using indicators in monitoring the condition of this broad-scale, unique, and threatened system (Wisdom et al. 2003; Finch et al. 2016).

An interactive and vital relationship exists between ecosystem diversity and functioning, and global biodiversity (Dasmann 1968, 1972); Wilson (1992); Cardinale et al. (2012); Reich et al. (2012); Hooper et al. (2012), and Noss (2013). Dasmann (1968) in a personal and ecologically-relevant journal, recorded the value and need for diversity for both humankind and the natural world, describing the connection between diversity and ecosystem resilience. E.O Wilson's (1992) *Diversity of Life*, raised attention to global biodiversity; the myriad complexity of the natural world comes from the pervasiveness and variety of species and ecosystems interacting across our Earth.

Ecosystems as Complex Adaptive Systems (CASs)

As a CAS, an ecosystem consists of multiple functional components which exhibit particular characteristics such as: adaptation, feedback loops, emergence, non-linearity, and self-organization (Levin 1998; Parrott and Meyer 2012; Odum 1988; Gunderson and Holling 2002; Folke 2006; Farnsworth et al. 2012). Classic works in the study of ecosystems as CAS include Levin (1998), Odum (1988), May (1972), Folke (2006), and Gunderson and Holling (2002). Further works which specifically describe ecosystem function, resilience, and diversity in terms of a CAS include Parrott (2010); Peterson et al. (1998); Tilman (1996); Tilman et al. (2014); Norberg (2004); and Farnsworth et al. (2012).

Characteristics of CASs

The characteristics and qualities of a CAS determine its function and diversity. One quality of a CAS is "emergence," in which a system functions as more than the sum of its parts (Levin 1998). A CAS has various connections and interactions, and exists in a non-equilibrium state of various self-organizing (adaptive) processes (May 1972; Levin 1998; Gunderson and Holling 2002; Parrott and Meyer 2012). Gunderson and Holling (2002) used the term "robustness" to describe the spatial heterogeneity and functional diversity of a CAS. System resilience is supported by this complexity and diversity (Folke 2006).

New pathways (such as changes in dominant species food web patterns or keystone species) occur in a CAS (Levin 1998; Gunderson and Holling 2002; Rietkerk et al. 2004). Redundant cycles and the ability for interactions to change as a system evolves and develops ("nonlinearity") supports adaptation, variability, and persistence of function (Levin 1998).

The persistence or stability of a CAS, does not imply a stationary or unchanging condition. An ecosystem exists between states of disturbance and recovery. Shifts between alternative stable states, also called bi-stability, (such as pineland to grassland or patch size dynamics) occur based on environmental conditions (Ghadami et al. 2018; van de Leemput 2018; Gunderson and Holling 2002; Scheffer et al. 2009; and Kefi et al. 2007; Filotas et al. 2014). Processes that influence ecosystem condition, such as system perturbations, recovery rates, and tipping points, are presented in Scheffer et al. (2009); McCann (2000); Rietkerk et al. (2004); van de Leemput et al. (2018); and Ghadami et al.

(2018). A tipping point is the shifting away from the resilient alternative-stable state to a novel, less-resilient condition (Scheffer et al. 2009).

Research on landscape-scale assessments describing the complex functioning of ecosystems, feedback loops, emergence, and biodiversity, includes Mouquet et al. (2013); Puettmann et al. (2016); Pellant et al. (2018); and Herrick et al. (2019). Because of the inherent complexity, much of the research towards understanding CAS function, including landscape-scale functioning, occurs through statistical modeling, rather than with on-the-ground research. The use of models allows for the analysis of a number of variables and possible interactions of species (most-often plants) to help define functional-environmental trait relationships. The challenge in describing a functioning CAS remains, even in models, is in the ability to fully capture the numerous variables; to identify the value or influence that each variable contributes to the system; and the interconnected influences these variables have among one another (Roy et al. 2019; Soliveres et al. 2016; Bowman et al. 2015).

Interdisciplinary, integrative, and synthetic approaches are being utilized to describe landscape complexity, function, or phases of ecosystem recovery (Bowman et al. 2015; Herrick et al. 2019; Zahawi et al. 2015; Riedler et al. 2015; Bennett et al. 2005). Methods-synthesis includes the integrative use of varied methods and sources such as paleoecology, historical data and knowledge, expert input, narratives, remotely-sensed images and processing methods, long-term monitoring and field experiments, and models. Bowman et al. (2015) introduced a five-step synthesis research approach in understanding the complexity of landscape dynamics, incorporating the use of metastatistical modeling with other integrative methods to detect landscape-level feedbacks. Per Bowman et al. (2015), "no single step is sufficient in itself to demonstrate the existence and strength of landscape-level feedbacks." The five-steps include: master narratives; conceptual models; correlative studies; field experiments and; longitudinal studies and historical ecology. Another integrative approach, by Herrick et al. (2019), utilized a combination of information that included expert solicitation, remote sensing data, and soil prediction models to define a soil-specific reference for rangeland health. In comparison to a single method approach, authors found these "methods-synthesis" approaches in landscape-function assessments to provide more descriptive measures and understanding of system complexity.

An improved understanding of landscape dynamics, and effective methods for assessing landscape condition, can contribute to improved descriptions of global biodiversity health (Bowman et al. 2015; Staver et al. 2011; Hirota et al. 2011; Pulla et al. 2015). Pulla et al. (2015) assessed globally seasonally dry tropical forests (SDTF) and the link between ecosystem health and biodiversity components (genetic, organismal, and ecological). Hirota et al. (2011) and Staver et al. (2011) considered critical transitions between tropical forest and savanna systems and system resilience at a global scale through the identification of regions that are most (and least) susceptible to tipping points. Critical transitions are the shifting away from the resilient alternative-stable states between forest and savanna, towards a tipping point, and a novel less resilient and less diverse, irreversible state, such as a treeless or overly dense-canopied forest. The multi-state stability (such as the forest-savannah complex) was shown to provide more resilience and diversity to a system than a novel state. Global climate processes, such as shifts in precipitation and temperature seasonal patterns and levels, also influence CAS landscape properties across a globe scale (Carter et al. 2018).

Indicators of diverse ecosystems.

Measuring the complexity of a CAS has its challenges (Anand et al. 2010; Corbane et al. 2015; Funk et al. 2017). Field research evaluating ecosystem condition is challenged logistically in the ability to comprehensively measure CAS processes and system functional complexity, and studies considering CAS-concepts and processes as a measure for ecosystem condition are limited. However specific CAS conditions have been identified as indicators for ecosystem diversity and resilience (Peterson et al. 1998; McCann 2000; Proulx 2007; Tilman 1996; Tilman et al. 2014; Farnsworth et al. 2012; Pulla et al. 2015; Rowland et al. 2018). Tilman et al. (2014), and Proulx (2007) indicated that species richness is not per se, the stabilizing factor of ecosystems, but rather it is the variety and scale of functional groups developed from species richness that builds system diversity and redundancy. And, it is this cross-scale functional redundancy that builds and supports system persistence and stability (Peterson et al. 1998; Farnsworth et al. 2012; Bennett et al. 2005).

Pulla et al. (2015) suggested that the persistence of functional groups is more important than species composition for the resiliency of the SDTF. Examples given by Pulla et al. (2015) in measuring biodiversity components included seed dispersers, pollinators, mutualists, and soil biota. Biodiversity components (genetic, organismal, and ecological) can be recognized as a characteristic of a CAS, and be used as an indicator of ecosystem resilience (Pulla et al. 2015; Robertson 1962). These biodiversity components function as an emergent property of the SDTF system.

Ecosystem functional modeling is being used to define and characterize the complex groups of indicators and their relationships within large-scale ecosystems such as wetlands, rangelands, and grasslands (Soliveres et al. 2016; Roy et al. 2019; Funk et al. 2017). Roy et al. (2019) examined plant functional traits as indicators for ecological condition and found that local and landscape wetland disturbance gradients can be identified using plant functional traits as indicators. A large-scale modeling study of grasslands by Soliveres et al. (2016) found that primary producers, herbivorous insects, and microbial decomposers were particularly important drivers of grassland ecosystem functioning, noting that focusing on a single trophic (food web) group can underestimate the functional importance of biodiversity.

The comprehensive work of Herrick et al. (2019) and Pellant et al. (2018) developed a strategy and quantitative framework, "Interpreting Indicators of Rangeland Health" (IIRH), for defining soil and climate attributes in the assessment of the vegetative health of rangelands in the western United States. Herrick et al (2019) built on the Pellant et al. (2018) framework in describing a strategy and protocol for defining a historical reference. Herrick et al. (2019) wrote the "most sophisticated approach to defining reference conditions uses a combination of potential natural vegetation and remote sensed-based imagery indices together with modeled predictors." This more-qualitative approach is based on the integration of scientific experts and data.

Specific studies in determining or selecting ecological indicators also include Proulx (2007), Bennett et al. (2005), Nicholson et al. (2015), and Kontula and Raunio (2009). As a CAS, one indicator of ecosystem health is the system's rate of recovery after a disturbance (Ghadami et al. 2018). An increased time for the system to return to condition after a perturbation (such as recovery after a fire or stochastic event) has been identified as an indicator of system collapse (Scheffer et al. 2009; van de Leemput et al. 2018; Ghadami et al. 2018). Information of an ecosystem's pre-transition or undisturbed state is useful for effectively measuring recovery rates (Ghadami et al. 2018; Rietkerk et al. 2004).

In trait-based ecology, traits influence community function. Funk et al. (2017) described how trait-based ecology may influence ecosystem condition, using predictive modeling of species plant community function. According to Funk et al. (2017), "variation in plant trait values within communities can predict the resilience of ecosystem functioning to disturbance." That is, species can influence community function; however, the authors' conclusion was followed with caution because underlying differential responses are known to occur within functional groups (Funk et al. 2017).

Components of biodiversity (species and suites of species) work as an emergent property to ecosystem function, and specific characteristics of suites of species may be used as indicators of ecosystem condition. System redundancy in a grassland system is exhibited through presence of a functionally, diverse herbaceous ground cover. The ground cover (mosaic) functions as a whole, and influences system function and health more than one species alone. Parr et al. (2014), identified endemic grassy habitat as a useful indicator for "tropical grassy upland areas." A distinct suite of vascular plant species, dominated by flowering plants (of both the superrosid and superastrid clades), ferns, gymnosperms, and a lycophyte species are identified and described in the S FL PR system (Fairchild Topical Botanical Gardens [FTBG] 2017; Trotta et al. 2018; USFWS 1999; Possley et al 2008). High endemism and strong phylogenetic relationships have been identified with this suite of species (Trotta 2018; USFWS 1999).

Simple model approaches and systematic guides for identifying indicators in complex systems and assessing resilience can be modified to identify resilience indicators for evaluating ecosystem condition (Puettmann et al. 2016; Messier et al. 2015; Bennett et al. 2005). A relatively simple systems-model approach for determining surrogate variables for ecosystem resilience (of a CAS) was developed by Bennett et al (2005). Socio-ecological case studies were used by Bennett et al. (2005) to illustrate a basic, four-step process for use in measuring the resilience of a natural system. Similarly, an instruction document on CAS concepts and applications in forestry management developed by Puettmann et al. (2016), included a list of questions to use as a guide for identifying key components for use in ecosystem assessments. Queirós et al. (2016) developed a basic ranking and scoring framework to test the effectiveness of indicators chosen to assess marine waters.

Mouquet et al. (2013) described a broader application of the keystone species concept to ecosystems. Ecosystems are themselves CASs, but they also exist and function within a complex, interconnected network of regional communities (a metaecosystem). According to Mouquet et al. (2013), some communities or ecosystems within a metaecosystem similarly follow the concept of keystone species and play a role as a "keystone ecosystem." The keystone ecosystem was described as one which contributed a regional influence or weighted role (such as for productivity, species recruitment, or species diversity) across a metaecosystem, and if removed would have a disproportionate or atypical impact on the broader regional landscape. The modeling results by Mouquet et al. (2013) indicated that a) the keystone concept could be scaled-up and applied to ecosystems, and b) some ecosystems were more important to regional properties than other ecosystems. The authors suggested further study was needed to find "general community properties" by extending the idea of "multi-functionality" to whole communities and ecosystems within a complex landscape.

An evaluation is only as effective as the indicators chosen (Queirós et al. 2016), and identifying and selecting effective indicators for ecosystem evaluation has many uncertainties and remains a major challenge. The emergent nature of numerous indicators is difficult to define even with meta-analysis modeling. Indicators and suites of indicators are used to evaluate and describe ecosystem condition, but do not capture the complete picture of system complexity. For this reason, an integrative process that synthesizes multiple-source data and uses a multi-disciplinary approach can be applied to most effectively identify a diverse set of indicators and evaluate ecosystem function.

Fire, Biodiversity, Grasslands

This section of the literature review will include pertinent works on fire as a landscape process, supporting system biodiversity, the role of fire in grassland habitat;

and fire behavior in context to the S FL PR (grassland) system. This review section is not meant to be a comprehensive review of fire ecology, or fire management science.

Fire - an integral process in a CAS

Frequent fire, forest, and grassland, are intricately bound, occurring within a complex and interactive feedback loop characteristic of a CAS (Pulla et al. 2015; Parr et al. 2014; Bond 2016; Bowman et al. 2016; Hirota et al. 2011; Rietkerk et al. 2004). Fire is not incidental to, but plays an integral role in, the persistence and health of the alternative stable states between forest and grassland (Harper 1911; Robertson 1962; Holling 1973; Lodge 2010; Dantas et al. 2013, 2016; Noss 2018). Fire-adapted (also referred to as fire-prone or fire-dependent) systems such as open pine forests and savannas are meant to be dynamic.

Fire is an ancient, natural, earth-process, and one used and manipulated for many ages in various forms by humans (Freeman et al. 2017; Bowman et al. 2015; Parr and Andersen 2006; Harper 1911; Noss 2018). Sources of fire include, wildfires (lightening), and man-induced fire (including indigenous fire-use, prescribed burns, and sometimes, arson). Earlier works such as those of botanist R. Harper, and, and biologist Dr. W. Robertson, documented the critical role of fire in the dynamics and diversity of open pineland systems of central and S FL (Harper 1911; Robertson 1962). Their descriptions captured the complex function of fire in the system: fire's role perpetuating the dynamic functions between forest and open ground story vegetation (i.e., alternate stable states in a CAS); the resultant, diverse herbaceous ground cover that would appear soon after a fire event; and how fire's shaping of landscape vegetation would, in turn, shape the nature of the next fire event (landscape heterogeneity).

Fire, whether naturally- or human-induced, is considered a key disruptive environmental driver of these dynamics that, in an appropriate form, spurs recovery and growth, and perpetuates diversity (Bond and Keeley 2005; He et al. 2019; Freeman et al. 2017; Bowman et al. 2016; Robertson 1962; Pausas and Keeley (2019); Dantas et al. 2016). Bond and Keeley (2005) described landscape fire as a 'global herbivore'. Robertson (1962) identified fire and hurricanes as the most effective factors on the vegetation patterns in S FL pine/grasslands, more so than edaphic conditions. Robertson (1962) cited the "controlling role of disturbance" as the check on succession and the largely determining factor of vegetative plant cover in the Everglades pine forests. Pulla et al. (2015) identified fire regimes as well as substrates as mediators in the co-occurrence and fluctuation between forest and savanna landscape condition in global SDTF. The burning of the landscape prevents the one-directional succession to closed forest or overgrown, dense mid-story by acting as a "regular check" on the system, and which allows dynamic alternate stable states to perpetuate (He et al. 2019; Pulla et a. 2015; Bowman et al. 2015, 2016; Robertson 1962).

Fire is not the only major environmental driver of the pine/grassland system. The functioning of the fire-dependent pine/grassland or savanna ecosystem relies on a set of complex interworking and adaptive components. Due to the inherent complexities of ecosystem function and fire processes, it remains a challenge to thoroughly characterize and define the role fire plays in the promotion and maintenance of system biodiversity

(He et al. 2019; Pulla et a. 2015; Bowman et al. 2016; Freeman et al. 2017; Driscoll et al. 2010; Parr and Andersen 2006; Noss et al. 2018).

Fire mosaic and biodiversity

Pyrodiversity

The concept that fire promotes biodiversity (pyrodiversity) caused a paradigm shift in fire science and management, and the concept has led to an improved understanding and integration of biodiversity goals into the planning and application of human-induced fire (prescribed fire) regimes (Freeman et al. 2017; Kelly and Brotons 2017; Bowman et al. 2016; Parr and Andersen 2006; Ryan et al. 2013; Noss 2018; Pausas and Ribeiro 2017). The concept of "pyrodiversity" was first coined by Martin and Sapsis (1992), who initially focused on fire patterns used by Native Americans. The concept follows that variation in fire across a landscape, results in a varied patch mosaic and heterogeneous landscape, promoting and supporting biodiversity. The term "patch mosaic" refers to the layers of burns on a landscape over time, producing a heterogeneous landscape (distinguished from a heterogenous fire; a single fire event that burns unevenly).

Fire research by Parr and Andersen (2006), Bowman et al. (2016), and Driscoll et al. (2010), primarily occurring within the large fire-prone landscapes of Australia, Africa, and S. America, has sought to identify if and how fire influences biodiversity. Freeman et al. (2017) provide a literature review on fire regimes in conservation, focusing on approaches used in North America. The research efforts, and applied fire programs, have identified challenges and uncertainties in designing fire regimes for the promotion and maintenance of biodiversity. Variable fire patterns referred to in today's prescribed fire practices are generally based on applying a combination of principles of fire science, existing knowledge of historic natural fire regimes (lightning-caused and seasonal climate patterns), and other ecological principles in ecosystem and species function (Freeman et al. 2017; Parr and Andersen 2006)

Bowman et al. (2016) expounded on pyrodiversity. They supported the concept of heterogenous patchy fire for promoting biodiversity, referring to the "feedbacks between fire regimes, biodiversity, and ecological processes." He et al. (2019) modeled variable fire regimes and their influence on biodiversity. He et al. (2019) found limits to the benefits of pyrodiversity in promoting biodiversity, and recognized constraints in modeling the correlations between the various components and ability to calculate the complexity of patch mosaics. Kelly and Brotons (2017) provide a succinct argument for the specificity or tailoring of fires for biodiversity. Freeman et al. (2017), with the incorporation of Kelly and Brotons (2017), concluded that pyrodiversity "cannot be translated into one simple management paradigm" and instead suggested a multi-faceted approach.

A broader, summarization of the "pyrodiversity" concept is, "a fire-induced state of landscape patchiness (patch mosaic) and biotic environmental heterogeneity which contributes to the maintenance or promotion of system biodiversity (Bowman et al. 2016; He et al. 2019; Freeman et al. 2017; Kelly and Brotons 2017).

He et al. (2019) provides a comprehensive summary of fire-biodiversity studies. Early works studying the pyrodiversity concept focused on determining the "level" or “amount” of variation in fire needed to maintain diversity, and tended to find no significant link between fire regimes and the maintenance of biodiversity. However, while results varied regarding the significance of pyrodiversity, the current widely-accepted view is that fire does play a role in the promotion and maintenance of landscape biodiversity (He et al. 2019).

The lack of consistent research findings regarding pyrodiversity may be explained in part by one or more of the following:

a) The variation of only a single fire component was used in the research. For example, “fire intensity” was used by Parr and Andersen (2009), with no significant effects found for diversity (as measured in ant species abundance). However, another component, or more likely, a set of manipulated fire components, could be more influential in supporting landscape diversity (Noss 2018). Shrub vegetation is known to be relatively resistant to variations in fire intensity, still, the frequency of fire, and the time since last fire, also referred to as the fire return interval (FRI), are found to impact shrub density. Depending on the type of system, range of environmental conditions, FRI, and the assessed variable (such as a specific species), the range of a manipulated fire-variable may not have been appropriate for producing a measurable effect (such as a fire-intensity range that is too low for a system that generally experiences more intense fire).
b) The difficulty in measuring the complexity of patch mosaics, heterogeneity, and the connections among the numerous fire components.

c) A wide range of tolerances in fire-variation exists for many fire-adapted species, therefore depending on the species being measured, effects to species may not be observed even after experiencing a broad range of fire-variation.

d) The focus is on a single species or taxon, rather than a suite of species, functional groups, or flora species for use in measuring fire effects, and;

e) The distributions and abundances of species are evaluated, but often the species' functional, structural, or temporal responses to fire that are not immediately evident or measured post-fire but which influence biodiversity were not fully considered (He et al. 2019; Parr and Andersen 2006). An example of this occurs in shrub species. The measure of shrub maturity, height, and branch thickness is not an immediate, post-fire measure. Mature shrubs occur approximately a year (yr.) post-fire. Generally, only during this time, do they begin to become associated with a reduction in herbaceous ground cover biodiversity and an increase in heavy fuel loads (Ratajczak et al. 2012; Robertson 1962).

Fire regime complexity

The complexity of fire processes and their role in system diversity does not lend itself to a "one size fits all" prescription. The components of fire include: frequency (FRI); intensity; seasonality; areal extent; and severity (Noss 2018; He et al. 2019). Fire severity is the fire's effect on the biota and landscape, and fire intensity refers to the physical components of the fire itself; the energy it releases (He et al. 2019; Noss 2018). Fire-adapted habitats have been characterized by the type of regime they are known to typically experience and be benefited. For example, the ideal fire regime described for S FL PR is a “stand-maintaining”, low-to mid-severity surface fire, characterized by frequent, low-intensity fire with a typical FRI of three to seven yrs. (Myers and Ewell 1990; Noss 2018).

The FRI, or both FRI and intensity, have been identified as a significant factor in grassland systems for maintaining or promoting diversity (Bond and Keeley 2005; Noss 2018; He et al. 2019; Robertson 1962). Peterson and Reich (2008) found species diversity was influenced by FRI in a forest-grassland system.

It is difficult to measure and prescribe fire to achieve system biodiversity directly. There are many uncertainties and unknowns about historic fire patterns to mimic (Parr and Andersen 2006; Hermann et al. 2015; Kelly et al. 2014; Lindbladh et al. 2013). Freeman (et al. 2017) reviewed existing literature on prescribed burns and the historical-fire regime (the mimic of natural fire regime in applied fire). No fire event is the same as the next; Fire occurs in the moment of time within a set of environmental conditions. Using variable fire events, a fire regime is meant to mimic natural variation that occurs with fire, rather than using fixed fire regimes with limited variability. The concept of heterogeneous and variable fire patterns being used on a landscape to promote diversity, and the value of uneven fire within a range of regime prescriptions (according to the type of natural system) that considers the FRI, levels of intensity, and timing are included in works by Kelly et al. (2014); Noss (2018); and Parr and Andersen (2006).

Variable fire over time produces a complex landscape that consist of a historical layering of burns. Over the course of time, these different burns, produce variation in the size and age of "patches" and in their pattern of overlap. This heterogeneity of the landscape structure and function is also dynamic; There is an "unevenness" and spatial overlap in the fire events, stages of recovery, and size and degree of patchy space. Further described, patch mosaics is the "layering of different 'aged' and sized patches, at various stages of growth and recovery from variable fire events that take place across a system over time" (Parr and Andersen 2006; He et al. 2019). Spatial niches are created within the different aged-patches and between burned and unburned areas. All support species in various levels of growth and abundance (resource partitioning) (Parr et al. 2004). This "successional process with different stages coexisting in space and time" facilitates diversity (Robertson 1962; Peterson and Reich 2008; Keeley and Pausas 2018; He et al. 2019). This fire-induced heterogeneity also provides for the species composition and fuel qualities and types that influence the subsequent fire.

He et al. (2019) modeled the complexity of patch mosaics. Results indicated that the net value of all the patches, current and previous (produced in a variable fire regime) is a measure of landscape heterogeneity. The measure of species richness was found to be the highest immediately post-fire. The modeling also identified limits to the size and number of patches (ratio of burned to unburned areas) in a given burned landscape for establishing a positive influence on diversity. That is, a limit to pyrodiversity. An increasing number of burned patches in a given area translated to a higher number of smaller patches and an eventual reduction in the number of available species that would allow for recovery and new recruitment. He et al. (2019) supported the restoration of "biodiversity-maintaining fire regimes" across broad landscapes.

Slocum et al. (2003) investigated the differences in patchiness and intensity of prescribed fires performed in PR grasslands of various elevations and ground layer moisture levels in the Everglades National Park (ENP). The frequent prescribed fire increased the patchiness of the ground layer (the preferred condition to support higher diversity). In contrast, infrequent burns with more evenly-distributed fine fuels, burned more evenly, and resulted in reduced patchiness. Slocum et al. (2003) also found that infrequently burned areas did not burn more intensely than frequently burned areas, due to the high moisture within a thick litter layer. Mature shrubs produced conditions of reduced fine-fuel and more shade, which translated to higher moisture in the ground cover. A significantly smaller proportion of submodules of shrub and palm burned in both low and higher elevation grasslands, because the fire was blocked from traveling across the landscape. Early-lightning season fires (when accumulated dry, fine-fuels were on the ground and before wet season) traveled readily through the drier, higher elevation grassland areas. In the ENP, "higher" elevation is measured by inches (in; centimeters [cm]) or a few feet (ft; meters [m]). In higher elevation grassland areas, fires were less-patchy and more intense, likely due to the drier conditions and pyrogenic fuels compared to later into the wet season. As wet-season progressed, fires resulted in patchier landscapes and less intense burns due to increase moisture within accumulated fuels. There was a higher abundance of shrubs and a decrease in the herbaceous layer as a result of off-season for burns. Slocum et al. (2003) recommended that prescribed burns mimic natural Everglades' fire (frequent, early lightning season) which vary in patchiness and intensity, to promote herbaceous ground cover; and increased plant diversity.

Variation in fire that more closely mimics the variability of how natural fires occur and burn across an open pine grassland or savanna system has been found more advantageous for promoting system biodiversity than a fixed and inflexible prescription (Hermann et al. 2015, He et al. 2019; Freeman et al. 2017). Variable prescribed fire regimes include variations in all or some fire characteristics, including frequency, severity, seasonality, areal extent, different weather and fuel-moisture conditions, and the use of heterogeneous ignition patterns (Ryan et al. 2013). Due to ecosystem fragmentation and the suppression of naturally (lightening) occurring fire events, variable fire is most often prevented from being a driving force for diverse and heterogenous landscapes. The challenge is to produce this heterogenous landscape structure through a prescribed, variable-fire regime. The principle of mimicking natural fire has been generally adopted through much of North America's prescribed fire programs, using the historical fire regimes concept (HFRC), and with a primary long-term goal of restoration in those fire-dependent systems that have, and still experience fire suppression (Freeman et al. 2017). Freeman et al. (2017) recommended a multi-faceted approach with prescribed fires, acquiring an understanding of historical fire regimes as well as biotic variables, and to resist narrowly defined fire rotations or those that measure just a single species.

Despite varied scientific results on pyrodiversity, the role of variable-fire in maintaining and promoting biodiversity in fire-adapted (fire-prone) systems has become a widely accepted premise (Ryan et al. 2013; Kelly and Brotons 2017; Freeman et al. 2017; He et al. 2019). Parr and Andersen (2006) summarized, "Fire is inherently heterogeneous.

Landscapes are seldom burned entirely, and fire behavior varies markedly within burned areas." This is especially for systems like the open pine grasslands and other frequently-burned systems (Hiers et al. 2009; Bowman et al. 2016; Kelly and Brotons 2017).

The determination of the "best" fire practices and regimes to be used to most effectively manage fire-adapted landscapes is an ongoing goal in fire ecology research. In principle, pyrodiversity involves the application of more flexible fire regimes in terms of seasonal, intensity, and timing variations in fire to create heterogeneous and dynamic-patch (varying in age, size, location) landscapes that support greater diversity. In practice, this goal is not being regularly or thoroughly achieved in many landscapes. Various reasons include the lack of program strategy, lack of application or incorrect application of scientific principles to fire planning, ineffective implementation of fire regimes, constraints from local fire policies, and a lack of resources (Kobziar et. al. 2015; Ryan et al. 2013). Fire management, as a discipline, continues to integrate ecological concepts and principles into fire science training. Additional research is needed on the results of long-term fire regimes that have applied and implemented biodiversity goals into their fire practices.

In summary, fire is an integral component on the pine/grassland (savannah) system, but as with any CAS, it is just one component of many interplaying variables. The extent that fire is contributing to the diversity of the system must also be considered in context to these other variables, such as climate conditions. In the function of CASs, variation of conditions promotes redundancies, which builds system resilience. Variable conditions, including fire that promotes a diverse and heterogenous landscape which then supports future variable fire events, act together within a feedback loop.

Fire suppression

A well-described historical reference to the use of the natural fire regime in prescribed fire management generally lacks, particularly in the forests of the United States. Since their inception, fire suppression (putting fires out) was the goal and culture of federal fire programs. Fire suppression practices continue to eliminate fire from many fire-adapted systems. As presented earlier, the understanding of the critical role of fire in these systems, fire ecology and science, and variable fire regimes are resulting in more commonly supported active fire events for managing and conserving these landscapes. However, due to the urban-forest interface, safety reasons, and the often lack of sufficient resources to regularly burn, fire suppression remains a threat to the health and persistence of the forest/grassland ecosystem.

Fire suppression decreases fire-induced heterogeneity (Robertson 1962; Bond and Keeley 2005; Bond and Parr 2010; Parr et al. 2014; Veldman et al. 2015; Bond 2016). Work by Parr and Andersen (2006), measuring small mammal abundance, reported significantly more diversity in burned landscapes than unburned. Parr et al. (2004) documented no significant differences in ant assemblages between different fires, but found a high resilience to fire of ant assemblages in burned versus unburned areas. Ant species richness was generally found to be lower in areas that had been unburned for long periods. Dee and Menges (2014) examined long-term (26 yrs.) fire suppression in FL scrub flatwoods, finding the loss of open post-fire patches, the accumulation of "impenetrable litter," and the consequent decline in species diversity. Long-term (30 yrs.) fire suppression in a diverse longleaf pine savanna was found to decrease fire-induced species heterogeneity, especially in herbaceous species richness (Palmquist et al. 2014).

DeCoster et al. (1999) found a decrease in species richness in plots in Everglades pine savannas (also called PR) that had been unburned for ten yrs. Fire suppression allows for the build-up of heavy, more mature vegetation that blocks the travel of fire (especially at a low-level through the ground cover), and perpetuates a system of shrub and hardwood and a heavy vegetative midstory that inhibits small forbs and grasses. Fire-adapted landscapes depend on fire to produce open space and light, promote rapid growth and stimulate seeding. The complex, patchy mosaic of a fire-landscape reduces competition, promotes redundancy in forbs and grasses species groups, and further produces a heterogeneous patchy landscape that supports system resilience and diversity. Even fire that is outside the parameters of the ideal fire regime (and is non-catastrophic), is still considered to be more beneficial than a lack of fire. Fire suppression eventually results in the loss of the forest/grassland system to a non-dynamic, novel state. Veldman et al. (2015) summarized, "The importance of fire on old-growth grassland systems cannot be overstated."

Grasslands

Grasslands are ancient, diverse, fire-adapted systems (Bond 2016). The current paradigm for the origin of grassland diversity is that it is an evolved characteristic with fire that occurred naturally in the grassland/savannah ecosystem, and not a result of human-induced fire or cleared forest (Bond and Parr 2010; Noss 2013; Parr et al. 2014;

Veldman et al. 2015; Bond 2016). Old-growth grasslands are considered ancient, "primary" grasslands. Grasslands that occur after deforestation of an area are considered "secondary" and often consist of different grass and plant species groups compared to old-growth grasslands (Bond and Parr 2010; Bond 2016; Veldman et al. 2015). The open-pine/grassland PR system is a primary grassland (see Section *PR Ecosystem; S FL PR*).

Parr et al. (2014) and Dantas et al. (2016) referred to the alternative stable states or transitions between forest and grassland (savanna) landscape conditions as "mosaics". Dantas et al. (2016) described the mosaics of "vegetation patches with contrasting tree densities" that provide for variable fuels and fire types within a landscape on a finer, spatial scale. The functional biodiversity and vitality of fire-adapted systems such as open-pine grasslands and savannas, is conditional to frequent burning; i.e., fire traveling across its landscape (Noss 2018; 2013; Harper, 1911; Myers and Ewel 1990).

Bowman et al. (2016) considered "fine-grained fire-mosaics" and the trophic links between species and species groups. The term, "fine-grained fire-mosaics" referred to the use of numerous, small fires (in space and time), compared to a few, large fires across that landscape. According to Bowman et al. (2016), the higher number of smaller fires produce a heterogeneous burn on the landscape and a higher number of unburned/burned patches (refugia and higher patch mosaic). This spatial and temporal heterogeneity of the landscape promotes higher biodiversity.

The forest and grassland exist as alternate bi-stable states at the global scale (Staver et al. 2011). Fire is a positive feedback mechanism in the grassland/savannah system. Fire-induced heterogeneity and the alternative stable state (multi-state) condition promotes system diversity and persistence (Bowman et al. 2016). Fire can spread more evenly through the open pine grassland than in a denser, more forested system, and can support the maintenance of the grassland understory. Staver et al. (2011) discussed how current changes in climate, specifically reduced wet season rainfall and the severe drying of the forest globally, will result in a shift to increased grassland/savannah systems. The concern presented by Staver et al. (2011) is the possibility of a permanent shift to one system (state). The conversion to one system and the loss of alternative forest and grassland stable states ultimately results in the decline and loss of global ecosystem diversity.

Noss (2013; 2018) consist of comprehensive and descriptive writings on fire history and ecology, with special attention given to the grassland component of the pine/grasslands systems in FL and the Southeastern Coastal Plain. Historically, most research and forestry management actions focused on the pine species. However, the significance of the grass understory and other characteristics of the (minimal hardwood midstory, and open canopy) that allow fire to travel through the system and instill species diversity into this open pine/grassland system, have long-recognized (Harper 1911). The PR is a highly-diverse ecosystem, with much of that diversity within the herbaceous ground cover. The grassland component of the open pine/grassland system is critical to the ecosystem function and a result of a millennia of frequent disturbance by fire (Veldman et al. 2015). Fire is a representative functional indicator of a healthy, fire-adapted, and fire-dependent pine-grassland system. A challenge continues to be the identification of critical fire and patch mosaic patterns that most effectively achieve system diversity. Fire suppression, or improperly-executed fire (long FRI, or highly-intense fire), may eventually cause heavy pine canopy and mid-story hardwood (shrubs/palmettos) to dominate the system. The system loses its open canopy, midstory growth dominates and displaces or shades the diverse herbaceous ground cover. The degraded system reaches an irreversible tipping point (Pulla et al. 2015; Hirota et al. 2011).

The fire cycle is in itself a CAS, and a critical component (indicator) to the functioning of the open pineland/grassland system (including PR). The results of fire are demonstrated in the condition and characteristics of that landscape. The history and regime of the fire are indicators to system condition. When present at its most effective form (for a given fire-adapted system), fire is a representation of healthy system function. The rapid, post-fire growth of the herbaceous ground vegetation minimizes the abundance of pine seedling growth, which helps to maintain the sparse open canopy of adult-pines. Fire promotes the reduction in hardwood mid-story species, and prevents those species from reaching mature sizes that do not burn well and inhibit fire intensity and travel across the ground. Hardwood reduction efforts attempt to mimic fire by opening up the mid-story and ground layers, but are not a replacement for fire. The complex fire cycle is the environmental driver of the persistent alternate stable state, open pine/grassland, conditions and the system's biodiversity.

The biodiversity in the grassland system is often inconspicuous at the ground level; much of the plant material of the herbaceous forbs and grasses occurs below-ground as roots and rhizomes (Veldman et al. 2015; Maurin et al. 2014; Small 1929).

Variable, low-intensity (and high-frequency) fire, opens up ground cover space and gives room for flowering grasses and shrubs to grow (Schmitz et al. 2002). Pyrogenic grasslands consist of fine, highly-flammable fuels that carry low- to mid-intensity fire across the ground (Harper 1911; Carr et al. 2009; Bond 2016). Ideally, fire returns periodically through the system before midstory shrubs and hardwood growth becomes too dense. When the system still has open lower or ground-story, the openness lets fire travel across the ground and prevents it from becoming too hot (damaging). There is also a seasonality to fire that provides for optimal diversity (Schmitz et al. 2002). According to Carr et al. (2009), the season of burning affects the relative abundance of shrubs but has little effect on species composition. The lack of fire allows for overgrowth, which smothers the grasslands, stops fire from traveling across the system, and breaks the complex feedback loop that supports the dynamic forest (tree density) and grassland (species composition) conditions. An "open pine system" means an open-canopy, and open-midstory system. The value of the pine trees in an open pine habitat includes a source of fine fuels (pine needles); structure and refugia, the capture of moisture and downpours, lightning ignition source, and in the high sunlight and hot, tropical systems, some degree of shade and temperature regulation.

The cyclical process of a fire-adapted system occurs across all geographic scales (Carr et al. 2009; Bond 2016; Veldman et al. 2015; Parr et al 2014; Wintle et al 2019; Pausas and Ribeiro 2017). The consideration of the health and contribution of the larger continental grassland and savannah biomes provide context to the significance of these systems to the dynamics of global biodiversity. Key works specifically characterizing large scale grassland systems include Veldman et al. (2015) and Parr et al. (2014). Parr et al. (2014) is a concise overview of the global tropical grassland biome (TGB). These works give attention given to the need to characterize and identify old growth savannah and grasslands accurately, and identify their significance as highly diverse and valuable global systems (Parr et al. 2014; Bond 2016; Veldman et al. 2015).

At the large, continental scale, TGB (described as primarily flammable C_4 grasses; open landscape with the prevalence of fire) are a significant contribution to global biodiversity. The global assessment of TGB, and the forest ground cover, has often been overlooked and compared to tree-focused forestry research despite the documented losses in global grassland systems and the negative consequences of this loss to global biodiversity (Veldman et al. 2015; Parr et al 2014; Bond 2006). Parr et al. (2014) suggested that TGB and threats to the savannah systems are overlooked because the TGB system's degradation is less visible than in forested communities (in addition to the historically-inherited importance placed on pine species and forests). Savanna and grasslands systems are often misclassified due to vegetation being described according to woody species, with the vegetation of the herbaceous ground cover rarely being considered (Parr et al. 2014). Parr et al. (2014) also emphasizes the need for further research of the grassland biomes because of their global contribution to Clean Development Mechanism (CDM), Reforestation Emissions from Deforestation and Forest Degradation (REDD +) processes, and global CO_2 emissions.

An improved classification of the TGB will assist in improving the definition of forest systems as applied to these global projects. As highlighted by Parr et al. (2014), the

Food and Agriculture Organization of the United Nations (FAO) vegetation classification method for identifying forest is structural-based (woody structure) rather than functional, and (highly biodiverse) ancient grasslands can be identified as "non-forested areas", and consequently identified and selected in these programs for reforestation efforts. Tropical grasslands naturally have some variation in woody structure, yet the REDD+ program uses the criteria of "loss of woody structure" in the determination of "degraded" systems. Targeting functional and diverse TGBs for "forest restoration" causes the conversion and loss of the TGB systems, resulting in fire suppression, and the loss of endemism, species diversity, and ecosystem function and services. Veldman et al. (2015) recommended developing international grassland polices, using old-growth grasslands to develop reference points and ecosystem-specific definitions. These same recommendations and suggestions by Parr et al. (2014) in identifying "non-forested"; "non-woody" structural components to better classify grasslands can also be applied to the PR ecosystem. Further evaluations and research on the health of savannah and grassland sites of all scales are necessary to build upon our global understanding of these systems and contribute to global projects such as with the IUCN Ecosystem Risk Assessment Program.

Numerous researchers identify the need for further work identifying and mapping grasslands (Parr et al. 2014; Veldman et al. 2015; Bond 2016; Pausas and Ribeiro 2017). Bond (2016) identified the need to characterize and map old-growth versus secondary growth grasslands, and suggested the use of satellite imagery to distinguish herbaceous understory and grass composition and measure functioning herbaceous ground cover.

There is a need to continue developing enhanced methods for assessing grassland systems, such as using UAS-derived imagery, and to integrate the information obtained for identifying the functional grassland systems, into these global programs. This integration can help improve the selection of land area and avoid the miss-selection of ancient grassland systems for reforestation projects, and further efforts to evaluate and conserve these systems.

Fire and Indicators

To identify healthy indicators for evaluating the open pine grassland system, it is necessary to assess the fire regime or patterns that have been occurring on that landscape. As mentioned, fundamental challenges exist in capturing the complexity of fire processes and functional biodiversity (Bowman et al. 2016). Fire prescription in current fire management most often includes operational guidelines and goals designed to promote biodiversity. A current challenge is in identifying the appropriate targets or indicators to measure diversity.

It can be advantageous to link fire outcomes to a representative biota, such as endemic species, but not base a fire regime solely on this indicator. Umbrella species may be used to represent historic ecosystem condition, such as the sage grouse umbrella species, for the western U.S. sagebrush ecosystem (Rowland et al. 2006). However, designing a fire regime to promote a particular host species can be limiting and problematic. By using a narrow measure for diversity such as one endangered species or single host plant (such as croton in PR), the variety of species responses and ultimately system biodiversity overall will quite likely not be addressed (Noss 2018; Parr et al.

2014). A narrow focus in a fire regime (set of fire events), or on a specific species could even be detrimental to other species that have different requirements for fire timing and seasonality; avoid strict and narrow adherence (Freeman et al. 2017). Instead, key functional groups, such as pollinators, indicate broader fire regime preferences and parameters (Carbone et al. 2019).

Ideally, a range of functional groups, species suites, or the life stages of a variety of fire-adaptive species should be considered to fire patterns. An ecosystem-based conceptual model and score sheet for rating the post-fire resilience of a Wyoming sagebrush site was developed by Miller et al. (2015). The resilience score sheet considered fire severity and primary components, or indicators, that influence system resilience, such as pre-fire plant groups (grasses, shrubs). Species indicators, functional groups, or a set of various biotic factors, can be used as "anchor points" to define the upper and lower ranges for prescribed fire goals (Freeman et al. 2017). Fire regimes are most effective when they work across trophic levels, life histories, functional groups, and scale (Magadzire et al. 2019; Freeman et al. 2017; Kelly and Brotons 2017; Carbone et al. 2019).

Carr et al. (2009) used a plot-sampling method using geographic, regional, and environmental variables to examine the grassland plant composition of Central and North FL pine systems. Modeling results by Carr et al. (2009) indicated that environmental variables (edaphic; mainly soil fertility) had the strongest influence on the plant composition of these forests. However, the authors suggest that historic constraints due to regional physiographic differences between the Peninsular (Central) and Panhandle

(North) FL region also influenced species composition. Soil fertility may act as an influencing variable to some degree, even for the PR system, characterized by an öolitic limestone surface substrate with very thin, and unevenly distributed soil areas. Specific modeling research on soil fertility and plant composition in the S FL PR system is lacking, but the structural component of the limestone substrate (solution holes, tiny crevices, and below-ground structure) also likely acts as an effective indicator, and possibly a more effective indicator than soil, per se, for the PR system (Small 1929; Noss 2013; Veldman et al. 2015).

Specific traits and functions of species in a fire-dependent ecosystem can be used as indicators to the system's condition, including the effects of a fire event on the system (Ames et al. 2017; Veldman et al. 2019). Ames et al. (2017) studied the functional traits of rare plants in a fire-dependent sandhill ecosystem and found that the range of strategies used by rare plants was "constrained" compared to more common species. The rare plants exhibited a) a "fast ecological strategy" of increased growth (allocation of resources to short-lived leaves, but which exhibited high photosynthetic capability), and b) short-flowering durations (adaptations to take advantage of the post-fire environment). These functional traits were consistent with those identified by Veldman et al. (2015) for old-growth grassland plant indicator species. In Ames et al. (2017), rare plants experienced higher than average maximum burn temperature (indicating fire-tolerance) and flame heights, which, according to Ames et al. (2017), are "measures of combustibility and fire promotion." Two examples of a rare plant genus cited in Ames et al. (2017) that exhibited the characteristics of "fast ecological species" included *Galactia spp*, (milkpea), and *Amorpha* (crenulate lead plant) (Austin 2015; IRC 2021). These two rare plant groups (with ESA-listed species) also occur in S FL PR, and exhibit the same or similar functional fire-adaptations related to rapid growth and short flowering duration. Ames et al. (2017) suggested developing a general framework that classifies species by functional properties instead of species identification alone.

A fire-adapted trait that apparently derived solely through the selective pressure of fire may have evolved through other selective pressures and variables (Keeley et al. 2011; Freeman et al. 2017). Freeman et al. (2017) used words of caution regarding the term "fire-adapted." Confounding and complex interactions that are not evident may be at play. An example provided by Freeman et al (2017) is the grass stage of pine tree species growth, once believed to have evolved as a selected protected mechanism for withstanding ground fire in the pines' early development, but since determined to have developed as a selective pressure to withstand drought conditions. The authors also cautioned on the misidentification or devaluing of certain species that are not historically identified in that "fire-adapted" assemblage but may also be valuable as indicators in the measure of fire effects and diversity.

Phylogenetics (species evolutionary history) is an expanding tool for examining trait diversity and composition, and in gaining a better understanding of the relationship between ecosystem processes and community pattern (Narwani et al. 2015). Species richness is often the metric used to describe or quantify system diversity (abundance and distribution) and ecosystem condition. However, an observed species community pattern is influenced by more than one process, and does not necessarily fully explain ecosystem function (Narwani et al. 2015). Variation in ecosystem function is not fully explained by species richness (Narwani et al. 2015), and large numbers of identified taxon do not necessary translate to greater genetic representation or functional diversity (Miller et al. 2018). For example, in a study of Australian native plant genera, Miller et al. (2018) found that, while there was a more significant number of genera for angiosperm plants than non-angiosperm plants, the angiosperm genera contained a smaller proportion of species genetic diversity (phylogenetic diversity (PD) (Faith 1992).

Venail et al. (2015) found no relationship between the PD of grassland plant species and community biomass production and stability and concluded that PD was not a better predictor of ecosystem function than species richness. Miller et al. (2018) concluded that PD was a better measure for biodiversity than species counts. Information on species richness and PD can be synthesized and applied together, rather than just one or the other being used as a predictor for describing community patterns and processes. Further research on the relationship between phylogenetic variability and trait variability is needed to understand the relationship between PD, biodiversity, and ecosystem function (Narwani et al. 2015). One specific question regards the finding of high group composition but low PD, and the implications this may have on ecosystem resiliency and stability.

Endemism represents the antiquity of grasslands herbs and forbs (Lodge 2010; Bond 2016; Noss 2018; Trotta et al. 2018). Many pyro-endemic plant species are characterized by smoke-induced germination and fire-stimulated flowering (Keeley et al.

2011; Keeley and Pausas 2018). The S FL PR habitat is represented by a high level of plant endemism (Trotta et al. 2018) that demonstrates fire-stimulated flowering.

The survival of persistent bud-banks, and below-ground budding are also characteristics found in fire-adapted/prone systems, including grasslands (Small 1929; Maurin et al. 2014; Pausas et al. 2018). Plant species' underground storage organs (geoxylic growth) are an intriguing nature of grasslands (Bond; 2016: Maurin et al. 2014; Pausas et al. 2018). These underground organs can survive surface ground fire in fire-adapted systems. Maurin et al. (2014) (with White 1976) defined geoxyles as those plants with "perennial below-ground wood root/stem, flowing and fruiting on seasonal and short-lived (resprouted) stems that do not exceed one meter (m) (3.3 ft) tall and occur in areas of high annual rainfall (above 750 millimeters [mm]) [30 in])." The evidence of geoxyles in fire-adapted systems is said to support the a) role of fire in grassland origin and b) persistence between fires of short stems in grassland vegetation (because most of the plant material is stored underground) (Bond 2016). Geoxyles are also referred to as "underground forests," or "underground trees," and have been predominantly identified and studied in the African savannas. Geoxyles have not yet been identified in the North American pine savannas. However, Maurin et al. (2014) suggested that this just may be due to a lack of recognition and that further consideration is warranted. Interestingly, three geoxyles mentioned in Maurin et al. (2014), *Ziziphus, Zamia, and Hypericum*, also occur in S FL pinelands.

Pine Rockland Ecosystem

An extensive library of literature exists for the PR ecosystem, particularly for the S FL PR habitat. Primary literature used to provide a general description of the PR ecosystem in this Section include: FNAI (2010); Snyder et al. (1990); Lodge (2010); Myers et el. (2004); Noss (2013, 2018); Robertson (1962); Harper (1927); Hoffmeister et al. (1967); Slocum et al. (2003); and Trotta et al. (2018).

The PR ecosystem is a highly-fragmented, globally critically-imperiled ecosystem with a limited global distribution (FNAI 2010; NaturServe 2021). The global extent of PR habitat consists of habitat in S FL, Bahamas (Andros, Abaco, Grand Bahamas, New Providence), Cuba, and Turks and Caicos (FNAI 2010; Myers et al. 2004). Despite this fragmentation and small global extent, the remaining PR system is known to support high diversity and endemism. The conservation value of small and fragmented habitats is becoming increasingly recognized for their contribution to global diversity. Increased efforts are needed to incorporate information about these smaller systems, such as PR, into global biodiversity conservation efforts (Wintle et al. 2019; Diamond and Heinen 2016).

Key characteristics of the PR system include: a) fire-adapted (fire-dependent); b) öolitic limestone substrate; with a spatially heterogeneous and minimal soil layer; c) diverse herbaceous ground cover with high endemism; e) sparse midstory layer of hardwood shrub primarily saw palmetto (*Serenoa repens*), and sabal palm (*Sabal palmetto*; cabbage palm); and, f) sparse slash pine canopy (*Pinus elliottii* Engellman var *densa*) (open canopy). The S FL PR experiences a subtropical, two season, wet and dry, climate, with a historical dry season from November to April, and wet season from May to October.

The open pine canopy allows sunlight to reach the predominantly shade-intolerant forbs and grasses and supplies pine needles which act as a source of fine, dry (flammable) fuel to the ground layer. The PR understory is an open and sunny habitat, but the pine trees and shrub/palmetto midstory layer still provide dimensional structure and supports microhabitats of moisture, shade, and shelter for insects to escape the tropical heat and torrential rains.

The slash pine canopy can withstand regular fire, but is generally too open to support crown fire, and the slender and splayed needles allow heat to be released in fire (Lodge 2010; Snyder et al. 1990). Based on information from ENP Long Pine Key PR habitat, the PR slash pine are approximately 20 cm (eight in), with a few trees up to 30 cm (12 in) in diameter, and stand density approximately 500 trees per hectare (ha) (202 per acre [ac]), with a canopy height below 24 m (78 ft) (Snyder et al. 1990).

The PR shrub layer is relatively sparse, a mix of palms and hardwoods, with a general abundance of saw palmetto and sabal palm (Small 1929). The palms and hardwoods are generally smaller in PR than in other environments due to the heterogeneously-distributed, thin soil layer, and fire events that prohibit hardwoods from maturing or developing thick branch height and diameter. Many shrubs have underground organs that allows them to be fire-resistant and re-sprout soon after fire (Small 1929; Hoffmeister et al. 1967; Bond 2016). Although these underground organs are not identified as geoxylic in PR, some of the underground growth of endemic and native shrub species may be able to be categorized as such.

Despite its defined land classification and name as a pine habitat, the system is more accurately described as an open pine-grassland system (FNAI 2010; Noss 2013). Grasslands are historically misnamed or misclassified as a forest-type (Parr et al. 2014). This pine-centric focus has changed over the yrs. with a greater ecological understanding of the system, and the contribution of such works as Noss (2013; 2018) on the Southeast Coastal Plains grasslands. The greater focus is now on the health and management of the PR as a grassland system, with a sparse, open pine canopy.

The PR is a dynamic system when experiencing fire: frequent, low-intensity fire of an every three-to-seven-yr. interval. Roberston (1962) described the system, stating, "The mosaic pattern of southern Florida vegetation cannot be explained by reference to variations in soil and climate, but are most effected by fire and hurricanes." The system is characterized by rapid recovery post-fire or -disturbance (hurricanes). Slocum et al. (2003), with DeCoster et al. (1999), found a return of fine fuels, primarily in the form of herbaceous ground cover and shed pine needles, within two yrs. Widespread fire suppression of the remaining forests and grasslands of the southern Unites States has produced habitat shifts from fire-maintained grasslands to shrub-dominated, "fire-impeding" forests (Freeman et al. 2017; Noss 2018). Managed, prescribed fire regimes are the primary source of fire to the PR system today.

Substrate and PR

The descriptive literature on limestone outcrops, soils, and plant communities in the southeastern United States includes Crow and Ware (2007), Baskin and Baskin (2004), Baskin et al. (2007) (Kentucky cedar glades), and a review by Lawless et al. (2006) on non-forested limestone prairies.

The PR system possesses a relatively unique öolitic limestone substrate. The substrate is an ancient, calcium carbonate coral reef that occurs globally in a few other locations, including the Bahamas, U.S. Mid-Atlantic States and Indiana, and England. Öolites are the small round particles of shell pieces or sand grains covered with calcium carbonate that over time are cemented together to form into the substrate.

Öolitic limestone (also called Miami öolite or Miami limestone in S FL) is the hardened but porous (highly permeable) sedimentary limestone formed during the mid-Pleistocene Age, in the most recent glacial period, and the primary surface layer along the S FL Atlantic Coastal Ridge and Southeast Florida (Snyder 1990; Hoffmeister et al. 1967; Davis 1943). According to Hoffmeister (1967), the S FL limestone began becoming exposed approximately 5,000 Yrs. Before Present (YBP), but Snyder (1990) suggested it may have begun much sooner based on archeological remains found estimated to be approximately 8,000 YBP. Snyder (1990) also cited the presence of calcium-loving endemic plant species with a long evolutionary history, which provides evidence to support the ancient history to the S FL pine savannas (PR). Based on Lodge (2010) and Snyder (1990), the development of (vegetative) habitat followed the exposure of the limestone (which occurred approximately 5,000 to 6,000, and possibly as early as 8,000 YBP); habitat which ultimately established into today's PR system.

The FL Coastal Ridge öolitic layer is approximately 11m (35 ft) thick at a maximum, and in southeastern Florida is only approximately three m (9.8 ft) thick (Hoffmeister et al. 1967). The substrate is very hard (noticed immediately by anyone who has stepped across it) but permeable, and can be softer below the surface. Areas of exposed limestone can be visible at the surface, particularly in the southern edge of the Coastal Ridge (where the study site is located) and depending upon the time since last fire (Harper 1911; Hoffmeister et al. 1967; Schmitz et al. 2002). The öolitic layer runs below sea level making it prone to saltwater intrusion inland and the below ground water table (and tree root system) (Ross et al. 2014; 1994). Existing literature on below ground plant traits and PR is presented in the Section, *Fire and Indicators*.

The ancient PR öolitic limestone substrate is an identifying indicator for the PR ecosystem, and a driver in functional plant diversity (Figure 1). This limestone substrate gives the system its "Rockland" title. This title is derived based on a lack of soil surveys in the Miami-area in the mid-1950's, which led to the use of the term "Rockland" to describe the "soil" type; and is the term used to this day (Snyder et al. 1990).

The limestone substrate weathers slowly over time, producing small crevices, indentations, and various-sized solution holes (also called sinkholes) in which organic materials deposit and support moist conditions (Baskin et al. 2007; Harper 1911). The öolitic limestone substrate is nutrient-poor; the exposed substrate is interspersed with

Figure 1. S FL PR exposed limestone substrate. LAQI WPT 21. West Indian Lilac (*Tetratzygia bicolor*). 2.4 m (8 ft) altitude.

areas with a thin surface layer of accumulated organic soil and fine fuels (pine needles). The porous nature of the limestone substrate allows for rapid drainage and minimizes standing water, except within solution holes. The amount and length of time that moist conditions exist or that standing water is held in the substrate depends on the size, depth, and connectivity of the solution holes, the amount of precipitation, and surrounding vegetation.

The PR surface substrate supports the diverse assemblage of hundreds of plants and forb species across just slight changes in elevation (microtopography) (elevation changes are a few cm [in] to a few m [ft]) (Schmitz et al. 2002; Crow and Ware 2007). Species take full advantage of the structural heterogeneity of the substrate and available microclimates of fine soils, decomposed litter, and moisture. Small (1929) described the roots of trees and shrubs buried in the erosion holes, and noted variation in PR vegetation types based on the microtopography. Everglades plants' topographic position was determined to be the strongest single predictor of species composition, but not a predictor of species richness (Slocum et al 2003; Saha et al 2018).

Schmitz et al. (2002) used a plot field-design to examine plant abundance in relation to the elevation change of the limestone substrate in the Everglades pine savannas (PR). Species abundance was found to be positively associated with elevation differences in 1m^2 (10.7 ft^2) and 10 m^2 (107 f t^2) plots. Topographical differences were determined by Schmitz et al. (2002) to influence the number of plants in a given area of the PR savannas, however, not to be the main driver for high plant counts in the habitat. Additional research in heterogeneous systems and the identification of microtopographic features as significant indicators of plant composition and patterns, include Alexander et al. (2016) (large, alkali grassland-mosaic mapping), and Sarkar et al. (2019) (diverse tropical wetland modeling).

Substrate and soil heterogeneity (age, nutrient level and availability, deposition) influences plant variation. The elevated pH (more "base"; towards a lower acidity level) produced by the limestone calcium carbonate increases organic matter turnover, and likely plays a role in plant turnover (Stern et al 2016).

The high diversity of the PR herbaceous ground cover consists of many calcareous-tolerant plants (Crow and Ware 2007). An example plant group with affinity to calcareous substrates are the *Euphorbia*, a large group of flowering plants, many of which are endemic to PR (Stern et al. 2016). The *Euphorbia* (spurges, sandmats) are rare species, but are abundant plants in the S FL PR habitat (IRC 2021). Approximately ten native *Euphorbia* species occur in S FL PR, including the study site, Navy Wells (IRC

2021). Two endemic *Euphorbia* taxa are the, *Chamaesyce deltoidea* ssp*. pinetorum* (pineland deltoid spurge; or pineland sandmat), and the *Chamaesyce deltoidea* spp. *deltoidea* (wedge sandmat); globally imperiled, Federally-listed threatened and endangered species, respectively, and State of Florida-listed endangered species (IRC 2021). The pineland sandmat, is present in the Navy Wells study site (IRC 2021).

Conceptual modeling by Laliberte´ et al. (2013) identified the influence of edaphic conditions on plant diversity in large grassland and tropical shrub systems, specifically soil age. Results indicated that aged and weathered substrate across different climates were associated with species-rich communities, however, this soil development work by Laliberte´ et al. (2013) did not specifically include study of the öolitic limestone substrate. Possley et al. (2008) found that the major soil type, regionally differentiated along a latitudinal (i.e., north to south) distribution in the S FL PR preserves, strongly influenced species assemblages.

Historical and current agricultural and forestry land use of the S FL PR habitat include tilling and raking practices that have resulted in structural disturbance to the limestone surface in many PR locations. Prescribed fire and hardwood removal activities using heavy equipment and vehicles and fire breaks have also disturbed the limestone surface. This disturbance and substrate break-up undoubtedly increases the weathering of the limestone, which allows more rapid and increased levels of rain absorption into the substrate (Laliberte´ et al. 2013). The accumulation and distribution of litter and fine organic material at the surface also changes in relation to the increased amount of broken limestone and small crevices across a site. Whether or not this process affects plant species assemblages and distribution, available fine fuels, and/or fire movement across the surface calls for further research. While Laliberte´ et al. (2013) indicated a strong role in soil age and weathering in plant diversity, the authors clearly note that plant species diversity is the result of multiple drivers. This is consistent with trends toward examining plant diversity as influenced by multiple, co-existing, and co-functioning mechanisms (Price et al. 2019).

The öolitic limestone substrate is an under-studied component of the PR ecosystem. Further research is needed in the relationship of limestone substrate structural and edaphic conditions to PR health and diversity.

South Florida PR

The S FL PR habitat is the interior-most vegetation zone along the Atlantic Coastal Ridge, also identified as the Miami Rock Ridge in S FL (Ross et al. 2014). The S FL PR ecosystem extends in fragments along the Atlantic Coastal Ridge. Highly fragmented, less than two percent is estimated to remain of the once approximately 74,900 ha (185,000 ac) (URS 2007; FNAI 2010; FWS 1999; Bradley and Martin 2012) (Figure 2). The system is designated under the Natural Heritage Ranking with a G1/S1 Global and State rank; critically endangered and rare (FNAI 2010; NaturServe 2021; FWS 1999).

The ENP Long Pine Key is, by far, the largest intact PR habitat (approximately 24,500 ac; 9915 ha). Outside of ENP there are approximately 30 PR parcels (preserves) and an additional five preserves of mixed PR and hardwood hammock that are owned and managed by the Miami-Dade (M-D) County Environmental Endangered Lands (EEL)

Program. The M-D County EEL Program is an environmentally endangered lands program that identifies and secures lands under public ownership for preservation (M-D County 2021). The remaining parcels outside of ENP and under the EEL program range in size between 1.6 and 92 ha (four and 227 ac) (Diamond and Heinen 2016) (Figure 2). Half (15) of these PR parcels are less than 10 ha (25 ac); three are greater than 50 ha (124 ac). An estimated 680 acres of PR habitat within 114 parcels (fragments) is reported in private ownership (Institute for Regional Conservation 2004 unpublished data: In Bradley and Martin 2012).

The study site, Navy Wells Pineland Preserve (Navy Wells), is designated by the State as one of four exemplary S FL PR sites. Navy Wells is a total of approximately 130 ha (322 ac) of PR habitat consisting of 92 ha (227 ac) M-D county-managed lands, and 38 ha (95 ac) held by the State of FL as part of the FL Keys Aqueduct Authority. Navy Wells is one of only three PR sites outside of ENP that is larger than 50 ha (124 ac), and the largest remaining M-D EEL Conservation Parcel (M-D County 2014; FNAI 2010). The site is described further in the *Methods* Section.

The S FL PR habitat is characterized by two regions (Biscayne and Redlands) from north to south, respectively, along the Miami Rock Ridge based on slight climatic gradients and soil differences between these areas. These differences are reflected, for example, in variations of palmetto shrub abundance (more abundant to the north), exposed limestone (more exposed in the south), soil conditions, and species composition between parcels (Snyder et al. 1990; Li 2001; Possley et al. 2008). Although

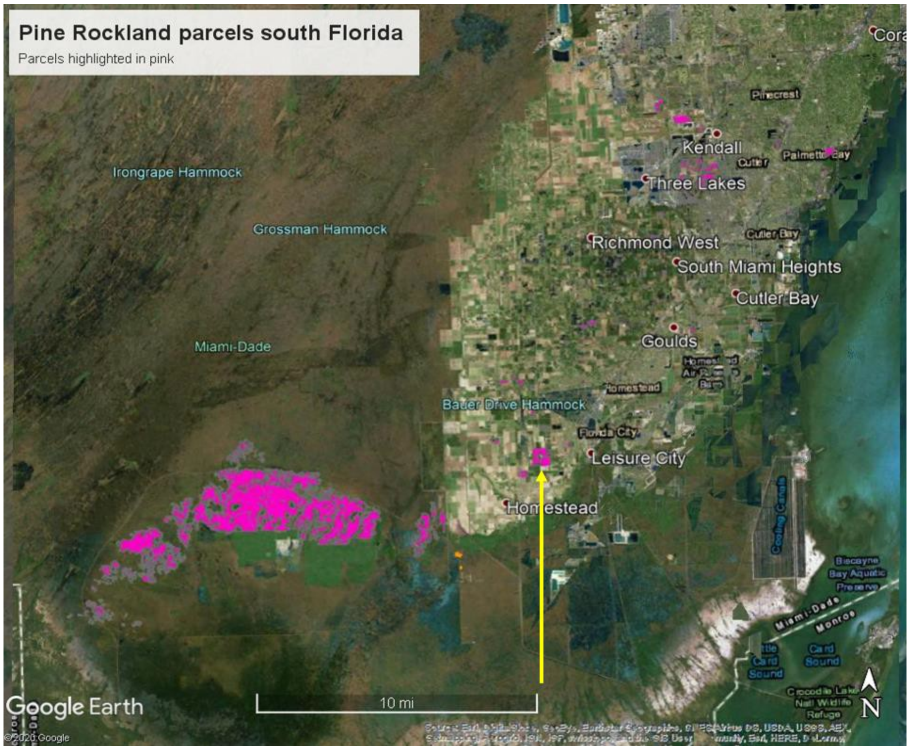


Figure 2. PR parcels, S FL, USA (shown in pink). Arrow identifies the research study site at Navy Wells; 130 ha (322 ac).

other factors, such as fire and management actions, also influence the variations that occur between parcels.

The S FL PR has a mostly flat (micro-) topography, with a narrow elevation range of approximately three to seven m (9.8 to 23 ft) above sea level, and described by Schmitz et al. (2002) as having "fine topographic variation." The low-intensity ground fires of this system produce small-scale open areas at the substrate level, and the, ideally, high-frequency of fire prevents or reduces heavy shrub and large vegetation. These fire characteristics are a critical positive factor in the small-scale environmental variation of this system (Schmitz et al. 2002).

The study site occurs on the southeast end of the Atlantic Coastal Ridge in the lower half of the Ridge in the area referred to as the Redlands, known for the red clay-soil that accumulates in depression areas over the limestone (Li 2001). The soil is much less-sandy than the PR habitat in the northern parcels (Biscayne Region). The PR habitat in this southern (Redlands) area tends to have more exposed limestone, with a shallower, more patchily-distributed, soil layer than PR in the northern parcels. Most PR soil is a basic pH consisting of approximately 30 to 50 percent organic material, as found in the limestone holes and crevices. In the Redland PR, the soil is slightly acidic, consisting of less than ten percent organic material (Snyder 1990; Small 1929). These differences, such as the exposed limestone, help to explain the higher level of calcareous-loving tropical plant species found in the Redland PR parcels.

The majority of PR habitat parcels have a history of being impacted by early pioneer family farming (Li 2001). Intensive logging began in the late-1800's with the presence of the railroad and continued until the mid-1900s. According to Snyder et al. (1990), the most impactful practice to PR was modern agriculture, mainly row-crop, grove farming that began around 1950 with the development of the "rock plow," a device that crumbled the limestone substrate. Progressive disturbance and destruction through commercial agriculture practices (including the use of mechanical rock plows) and human development continue to this day, resulting in the direct loss and conversion of natural PR habitat to residential development and agriculture.

Small (1929), in his travels through S FL PR, documented strong concern for the destruction he was observing of the system through the fire that was used to clear the land for agriculture and homesteading. Smith (1929) recognized the destructive use of fire by man for these purposes, and noted the value of fires as a positive, constructive natural process. Robertson (1962) also raised the alarm decades ago about the rapid degradation of the S FL system.

While the ecological indicators (such as diverse herbaceous ground cover) and processes (such as fire-dependence) of grassland systems apply to the S FL PR/grassland system, the PR ecosystem in S FL is not spatially functioning as the vast, unbroken grassland savannas of Brazil and Africa. Instead, this entire system can be likened to many endangered "species" (in this case, systems) that consist of small, fragmented, remnant populations (parcels in the case of PR) (Figure 2) and that are functionally compromised in their survival due to this fragmentation. The largest remaining and most intact parcel, Long Pine Key, is protected within ENP. As described earlier, the remaining thirty parcels in S FL and outside of ENP, are primarily conserved through the M-D County EEL Program, and managed by M-D County Environmental Resources Management (DERM) (Diamond and Heinen 2016; Bradley and Martin 2012). Today, there is a highly active scientific and local volunteer, community organizations, such as the Connect to Protect, working to protect and restore remaining S FL PR (Connect to Protect 2021). Possley et al. (2014) developed a vegetation monitoring guide for S FL PR restoration, supporting the use of manual hardwood clearing and hardwood estimates to help prioritize and initiate first steps in fire suppressed and degraded PR habitat. Additional work describing the conservation strategies and local M-D County management protections for S FL PR system include Possley et al. (2018; 2020), Duncan et al. (2020), and Jones and Koptur (2017). Possley et al. (2018) developed a comprehensive management and land use plan for the urban Richmond Tract of PR (including Miami Zoo), located in the Biscayne Region of the S FL PR, and an area experiencing intensive local development pressure. A PR Business Working Group consists of the contribution and participation of individuals from Federal, State and local government agencies, NGOs, and local businesses; species experts; land managers; and private stakeholders to protect and restore remaining parcels. The group's efforts include compiling existing data for the assessment and ranking the remaining S FL PR parcels to develop a PR Business Plan. The Plan will use biological and economics data to strategically guide potential recovery and/or purchase efforts. This effort emphasizes the reality of the situation for this highly-fragmented, critically endangered ecosystems and the necessity to triage the few remaining parcels. Other separate inventories and assessment programs have been completed for the S FL PR system to focus on species conservation, conservation land acquisition, or quality scoring to determine value for tax assessments (M-D County 2014).

Climate threats, including sea level rise and saltwater intrusion in S FL are converting coastal communities and eventually upland forest, such as PR, to salt-tolerant, mangrove-dominated systems (Saha et al. 2011; 2015). The PR habitat is experiencing transition and loss of habitat quality before what is expected to ultimately "shift" to a mangrove system. Present symptoms to this are, 1) groundwater saltwater intrusion (saltwater inundating into the limestone subsurface and root zone at times of severe storms), 2) accelerated changes to the S FL seasonal rainfall, and 3) temperature patterns producing wetter dry-seasons and drier wet-seasons with consistently warmer temperatures, and the increase in the number of severe storms impacting the region (Carter et al. 2018; Settele et al. 2014).

Small (1929) provides early notes on the character of the S FL PR habitat as he traveled through the area, noting abundant small shrubs including locust-berry, coco-plum, *Myrsine,* and poison wood. There was an early understanding of the strong representation of endemics in the system; Robertson's (1962) early characterization of the flora was a "haphazard assortment" of West Indian plants. As mentioned, Noss's (2013; 2018) works have focused on a comprehensive description of the PR ecosystem as a grassland and open pine canopy system.

While today fragmented, the PR ecosystem remains one of the most unique and diverse pine-grasslands systems because of its öolitic limestone substrate and high number of native and endemic forbs and grasses. Within the remaining parcels, the S FL PR system supports high plant species richness (DeCoster et al. 1999; Schmitz et al. 2002; Possley et al. 2008). Decoster et al. (1999) found high species richness at all spatial scales (1m [3.3 ft] to 0.1 ha [0.25 ac]) in Everglades pine savanna (PR). Even small (m^2 plots) of PR have been shown to support high native plant species richness (DeCoster et al. 1999; Schmitz 2002; Possley et al. 2008; 2014). There are over 400 identified plant taxa identified (mostly native) and approximately 47 endemic PR species; about 14 to 29 of these endemics are species restricted to PR (Snyder 1990; Trotta et al. 2018; USFWS 1999; Gann et al. 2009; Bradley and Martin 2012; Possley 2008, 2014; FTBG 2017). The

Institute for Regional Conservation (IRC) identifies a total of 382 plant taxa for the Navy Wells Pineland Preserve study site (IRC 2021).

An invaluable and readily-available online database and search engine for S FL flora, including PR flora, is provided and maintained by the IRC (IRC 2021). PR has numerous federally- and state- listed endangered and threatened PR (endemic) species, and federally-designated critical habitat (USFWS 1999; USFWS 2018; Possley 2014; Gann et al. 2009). While they may be abundant in the PR habitat, these are rare species with restricted global distributions and under severe threats (USFWS 2014a, 2014b, 2015, 2016, 2017, 2018).

Key literature and sources providing detailed information on PR plant species, distribution, and composition used for this research include: Gann et al. (2009); Possley et al. (2018; 2014, 2008); FTBG (2017); IRC (2021); USFWS (2018); Austin (2015); and Trotta et al. (2018). A summarized list of woody plant species (shrubs) is provided by Snyder et al. (1990). The numerous Federally-listed and endemic PR species are listed in Appendix 1. Federally-listed species with designated critical habitat in PR include the, Carter's small-flowered flax (*Linum carteri* var. *carteri*); Florida Brickell-bush (*Brickellia mosieri*); and the Florida Leafwing (*Anaea troglodyte floridalis*) and Bartram's Scrub-Hairstreak butterflies (*Strymon acis bartrami*) (USFWS 2014a; 2014b; 2015; 2016; 2107). The USFWS is in the process of developing species status assessments and a PR habitat management plan to address recovery and protection needs for the PR Federally-listed species (USFWS 2018). Despite these individual ESA listings and critical habitat designations, losses to the ecosystem continue. Individual species listings and designations, and the regulatory interpretations and guideline constraints placed on the ESA law result in the piecemeal protection, at best, for the ecosystem.

Trotta et al. (2018) recently examined the phylogenic origins and relationships of the PR endemic grasses and forbs species. Results indicated that suite of endemic PR flora species are dominated by variety of flowering (monocot) plants, with representative species of both clades (superrosid and superasterid) (Trotta et al. 2018). The plant species are dominated by perennials (with rapid turnover; and many with brief life spans) (Snyder et al. 1990). The beach false foxglove (*Agalinis fasciculata*; Figure 81) and Rose-of-Plymouth (*Sabatia stellaris*) are the only two annuals that occur in PR. Snyder et al. (1990) also highlighted two species, Small's milkwort (*Polygala smallii;* biennial) and the Crenulate lead plant (*Amorpha crenulate*), that are represented in PR with just a few populations each. While not a plant species, a newly-discovered PR endemic species, the venomous PR Trapdoor Spider (*Ummidia richmond*) was recorded on April 2021, in the Miami Zoo S FL PR preserve (ZooMiami.org 2021).

Phylogenetically, the intersecting ranges of temperate North America and the tropical Caribbean taxa (New World regions) contribute to the mix and diversity of the endemic PR plants, with the tropical Caribbean contributing the most taxa to this endemic flora (Snyder et al. 1990; Trotta et al. 2018; Austin 2015; USFWS 1999). The Redlands PR habitat has more representation of tropical species than the northern Biscayne Region (Snyder et al. 1990).

Possley et al. (2014) compared S FL PR preserves, performing four yrs. of sampling, twice a yr., using plot transect sampling methods. Estimated percent cover, and species identification and abundance were documented. Possley, et al. (2014) also correlated herb diversity to hardwood density. A target litter depth of less than three cm (1.2 in) was identified for selected indicators, including plants with host species (such as the Croton; *Croton linearis*). Possley et al. (2014) found that a litter depth greater than three cm was indicative of fire exclusion. Preserves that experienced a fire within three yrs. of sampling had a target litter depth of less than three cm (1.2 in). Litter depth also explained 18 percent of the variation in native understory species. A negative relationship was found between native herbaceous diversity and both fire exclusion and hardwood density. Possley et al. (2014) described PR in "good condition" as having a patchy distribution of pines, palms, and herbaceous ground cover. Possley et al. (2014) discussed succession of PR habitat to hardwood hammock due to fire exclusion. This converted state still supports PR species composition, and seed banks, and can be returned to the open PR habitat with fire and/or management actions (alternate stable states condition). But, depending on the extensiveness of historical anthropogenic impacts, and other contributing factors, such as climate and surrounding edge effects, a permanent shift (critical transition) to an ecologically distinct, novel condition (with new species, such as invasive species, and function) results (Hobbs et al. 2009; Hallett et al. 2013). In this case, the recovery of alternative stable states and the ability in the once-functioning PR system to return would be extremely difficult (Rowland et al. 2018; Freeman et al. 2017; Veldman et al. 2015).

Historically, the view of fire in the S FL pine savanna systems was described in terms of a "fire-climax" that disturbed hardwood progression. Early environmental views followed the concept of "upland succession": a linear successional process ultimately that led from an open pineland system to the climax vegetation community of tropical hardwood hammocks (Lodge 2010; Alexander 1967; Harper 1911). The ecological focus was on the tropical hammock, and the trees and shrubs, and fire acting as a "disruptive force." Harper (1911) viewed the pine savannah's post-fire vegetation as "pioneer" species. It was noted by Robertson (1962), however, that the PR forests and fire on the system were not necessarily leading to a successional "uniform climax vegetation." Current ecological principles now describe the bi-stable, alternate state processes and the role of fire, in perpetuating the diversity of the pine/grassland system.

Typical fire characteristics for a grassland system include frequent, low-intensity fire (Schmitz et al. 2002; Noss 2018; Possley et al. 2014). Fire frequency for S FL PR is within a range of three to seven yrs. (Noss 2018), but the range is variable and can be broader. Snyder et al. (1990) reported on a two- to three-yr. time frame to allow for enough fine fuels to accumulate post-fire and a ten- to 15-yr. time frame for the herbaceous ground cover to be shaded-out. Possley et al. (2008), in a study of plant species richness in a variety of PR parcels between 1995 and 2003, found high plant species richness was retained in PR habitat that had not burned for eight yrs. The change produced by fire in S FL PR occurs at the landscape level; species composition mainly remains the same (most of the species can survive and regrow after fire), but the function of a fire is to shift the habitat from hardwood to herbaceous cover (Snyder et al. 1990).

This ideally occurs with enough fire frequency to prevent shifts to a mature, fire-resistant hardwood system.

Fire regimes coupled with hardwood reduction efforts are used to manage the S FL PR preserves (Maschinksi et al. 2005). The M-D Restoration Plan (Possley et al. 2018) presents a comprehensive plan that considers PR restoration targets, such as a “25 percent palm abundance with shrub gaps.”

Types of fire regimes, particularly prescribed burns, can act as indicators that provide insight on PR habitat condition. Robertson (1962) described fire in the pine savannahs as “creeping through” the system. Fine fuels are highly-flammable, burn low to the ground, and not as great a height as the mid-story shrubs. The structure of the grasses and rough limestone surface keeps pine needles loose and separated, rather than matted to the ground from dampness, which helps to keep the fire low-intensity, and able to spread across the ground without getting too hot or too high in flame height (Snyder et al. 1990). Seasonally, fuels become too moist as the wet season progresses, so the fire does not generally travel readily or evenly through the system during these months. However, the variability in fires within and across seasons ultimately provides for a structurally and temporally heterogeneous landscape able to support a mosaic of different plant species distributions, abundances, and age ranges.

Myers et al. (2004) identified numerous variables for defining the transitional stages or conditions of the Caribbean pine forests, such as the a) proportion of pine litter/grasses to shrubs and palms, b) grove size in proportion to canopy opening, and c) herbaceous ground cover. Multivariate factors have been identified as drivers in diversity in Australian grasslands (Price et al. 2019). The use of a myriad of information sources and samples, and their syntheses, are critical to capture the complexity expressed via different functions, structure, and scale (Manfreda et al. 2018; Lopez and Frohn 2018; Rowland et al. 2018; Lausch et al. 2018; Proulx 2007*)*.

The selection of indicators for measuring site-based ecosystem condition should also be considered for their capacity to operate as Essential Biodiversity Variables (EBVs) for monitoring changes in global biodiversity (Haase et al. 2018; Pereira et al. 2013). EBVs, defined by Haase et al. (2018) are, "biological state variables from the gene- to ecosystem-level documenting changes in biodiversity." Example EBVs of the PR ecosystem include a) endemism and diversity of grassland (herbaceous) ground cover; b) extent of system fragmentation; and c) fire regime.

Remote Sensing and the UAS

Remotely-sensed imagery has a strong but under-exploited potential as a resource for biodiversity assessments (Nagendra 2012; Murray et al. 2018). Acquired from various platforms (satellites, fixed wing aircraft, UASs), the imagery can provide historical views, time-series changes, and vegetation classifications, and be relatively easily incorporated into ecosystem evaluations. Online sites used to search for existing imagery for use in this research include: USGS Earth Explorer (2020); M-D County (2020); Digital Globe (2020); Google Earth Pro Open Access (Google Earth) (2020); FWC (2021); Gann and Richards (2013); Gann et al. (2012); and FL Department of Transportation (FDOT) (2020) (see *Methods* Section). Examples of readily-accessible, free, satellite imagery include Landsat (30 m, medium spatial resolution) and WorldView

(WV) (2m high spatial resolution) (USGS Earth Explorer 2020). The USGS is now uploading UAS imagery to their Earth Explorer site.

Differences exist between the types of acquired remote imagery. Global satellite imagery is typically large scale and with many repeated images acquired across the same location that are useful for comparative study. The satellite images need to be reviewed and filtered for cloud cover, particularly in subtropical/tropical areas such as S FL. Satellite images are generally multispectral (m-s; eight to 12 bands) imagery which include a Near-Infrared (NIR) band for vegetation index processing but can be large and cumbersome to download, and require adequate computer processing and storage space. Imagery from manned aerial flights can be specifically focused and designed to a regional scale, but flights depend on weather conditions, can be costly, are less energy-efficient than a UAS, and have a higher risk to human life. The UAS platforms can be flown at low altitudes, below the clouds; tend to be easy to use; and are capable of being flown in remote and hard-to-reach locations. The UAS imagery has high temporal resolution and is relatively easy to process (Laliberte et al. 2011). UAS flights are repeatable and can be adapted and tailored to project needs. The UAS is limited in range, however, compared to the satellite and manned platforms, and is dependent upon battery use, and weather conditions.

Zlinszky et al. (2015) discussed the value of remote sensing in quantifying biodiversity, and its ability to impact conservation and management, but also described a current problem in the rare use of integrating remote sensing into “local or regional biodiversity assessments.” Local- to regionally-scaled remote sensing imagery is useful for obtaining baseline conditions of habitats and protected areas, documenting species diversity, and identifying threats to a system (Nagendra et al. 2012). Specific habitat conditions, unique sets of plants, species associations, substrate type, and burned landscapes have patterns which can captured with imagery. Plant spectral diversity, derived from remote imagery, can be used with other measures of biodiversity, such as taxonomic and phylogenetic diversity, for determining ecosystem function (Schweiger et al. 2018). Schweiger et al. (2018) found spectral diversity as predictive of ecosystem function as taxonomic and phylogenetic diversity. Imagery data indicating temporal and spectral changes in patch sizes, or species mosaics, can provide evidence towards system shift or stability (Scheffer 2009; Schweiger et al. 2018; Riedler et al. 2015; Bennett et al. 2005; Kefi et al. 2007; and Murray et al. 2018). Corbane et al. (2015) supported the "tailoring" of remotely-sensed data to support conservation policy, such as the Aichi Biodiversity targets.

The discrimination between different-aged, heterogeneous fire footprints and variable patch patterns derived from remote imagery helps identify the spatial and temporal diversity of a site (Parr et al. 2006). Hiers et al. (2009) used remotely-sensed LiDAR (light detection and ranging) imagery to identify variations in fine-scale fuels and fire patterns that can help predict the effect of variable fire. Large scale, Moderate Resolution Imaging Spectrometer (MODIS) satellite imagery was used by Parr et al. (2014) to establish percent tree cover (a measure of landscape patchiness) across Africa to identify areas of degraded forest for use in the REDD+ program.

Studies using satellite remote sensing data in the classification and mapping of the Everglades include Madden et al. (1999); USGS (2004); Gann et al. (2012); Gann and Richards (2013); Gann (2014); Richards and Gann (2015); Zahawi et al. (2015); and Zhang et al. (2016). Zhang et al. (2016) used a combination of image data-types (aerial, hyperspectral, and LiDAR) to classify major plant community types in the Everglades, including PR habitat. The use of very high spatial and spectral resolution imagery (20 to 30 cm) was required to capture and differentiate the "high spatial and spectral heterogeneity" of small patches of vegetation cover that could not be clearly defined in the courser spatial resolution imagery (30 m or lower). Gann and Richards (2013) concluded that high spatial resolution imagery could be used for consistent, resampling of vegetation classification. The use of high spatial WV satellite data was shown to produce effective results in the mapping of ENP vegetation completed by Richards and Gann (2015). However, a disadvantage to the WV data was its lack of easy accessibility and the effort needed to acquire the data. To close gaps in reference information, Richards and Gann (2015) recommended that high-resolution aerial photography or extensive ground surveys and photographs be completed. The UAS platform is an effective tool for this purpose, and can supplement or replace the use of the more labor-intensive aerial photography and extensive ground monitoring methods.

Composite-imagery processing was used in Riedler et al. (2015) and Zahawi et al. (2015). Riedler et al. (2015) used LiDAR and vHR satellite composite imagery to examine tree composition and forest structure. Zahawi et al. (2015) used UAS imagery and advanced composite image processing to describe Everglades habitat types. Both studies found strong comparison between their composite results and expert-based maps.

Han et al. (2017) compared UAS and aerial (manned-airplane) acquired imagery. Results indicated that the UAS imagery was more precise than the aerial imagery for measuring vegetation change and could be explained by the increased precision in sensor/camera capabilities and the maneuverability and accessibility of the UAS platform over the habitat. The vHR UAS imagery allows for detailed discrimination of vegetation type and condition that can be readily acquired for use in real-time evaluation, and for identifying shifts or changes in ecosystem condition and function over time (Murray et al. 2018).

The UAS platform has become a regularly-used tool in forest biodiversity assessments. The processed orthomosiac images have been used to calculate vegetation distribution and individual species coverage (Manfreda et al. 2018; Cruzan et al. 2016; Getzin et al. 2012). Parr et al. (2004) identified the UAS as an excellent tool for mapping and monitoring fire. The UAS, local-scale imagery often bridges the gap between large scale satellite data and ground-based monitoring (Lausch et al. 2017, 2018). UASs are also capable of "collecting large amounts of information with minimal impact to sensitive habitats" (Cruzan et al. 2016).

Research gaps exist in the use of remote imagery to study the function and diversity of grasslands, including the herbaceous ground cover of a pine-grassland systems (Bond 2016; Parr et al. 2014; Veldman et al. 2015; Noss 2013). Bond (2016) supported grasslands mapping at a global landscape scale, often overlooked in favor of forestry mapping. The diversity and complexity of a grassland system, specifically the herbaceous ground cover and mid-story layer characteristic of the grasslands, are difficult to characterize in large-scale imagery. The earth satellite images often do not capture the understory characteristics below the forest canopy (Parr et a. 2014). Numerous crop and forestry research studies have also focused on the canopy structure or a single and predominant target species such as pine trees) within monoculture-type habitats (Schneider et al. 2008; Getzin et al. 2012; Zahawi et al. 2015; Zhang et al. 2016; Bagaram et al. 2018; Larringa and Brotons 2019). Remote sensing methods used in agricultural crop surveys are a valuable source of crossover methods for landscape and ecosystem surveys. However, the goal for agriculture and managed forestry is commonly to separate a monotypic main crop or tree species from the ground layer (often bare soil or weeds) (Shafian et al. 2018; Louargant et al. 2018; Roosjen et al. 2018; Dong et al. 2020). In contrast, the common goal in ecosystem evaluation is to interpret the diversity and variety of habitat types occurring within the system.

Getzin et al. (2012) was one of the first studies using UAS vHR imagery to examine a pine ecosystem's "understory" biodiversity, using images acquired from flights above the upper pine canopy. This top-down study examined the distribution of light across the area and tree gap patterns (aggregated versus dispersed) in correlation to plant diversity and found that tree gap measures had a strong relationship with biodiversity (defined as species richness). UAS flights routes over the tree canopy provide high-definition orthomosaic images, but most sensors do not capture the full-detail of the ground cover (mosaic) through the canopy.

In typical savannahs with sparse trees, or grassland forests with few trees, and a sparse mid-story (such as PR habitat), flights under the canopy using small UASs can capture the full-detail of the herbaceous ground cover. This method is much more feasible with the use of the highly-maneuverable small UAS platforms. At the time of this research, there were no published methods for using small UASs at low altitudes under the canopy, to acquire understory imagery of (PR) ground cover diversity.

Conservation science and habitat assessment methods are being influenced by the rapid advancement of UAS technological innovations and capabilities in platforms (reduced size and weight; interchangeable-sensor capability); high-quality sensor-types; and user-friendly imagery processing software (Cruzan et al. 2016; Lausch et al. 2018; Corbane et al. 2015; Nagendra et al. 2012; Zlinszky et al. 2015; Han et al. 2017; Murray et al. 2018). UAS flight survey planning and automated mapping apps are also readily-available and user-friendly (MapPilot Pro 2020; Pix4D 2018; DroneDeploy 2018).

Many of the most accessible and affordable UASs have RGB sensors that provide true-color (t-c) images. M-s sensors are usually larger (heavier) and more expensive than RGB sensors for use on UAS platforms. However, the m-s sensor is advancing in technology (small size and weight) and becoming more available on small UASs (Laliberte et al 2011). Modified m-s sensors, using infrared filters, such as with the MAPIR products, can provide m-s imagery; this is an affordable and adaptable option for small UASs (MAPIR 2020). Apps for UAS flight planning, airspace information, and filing Air Traffic Control (ATC) authorizations include: Air Map, and B4Ufly. It is up to the pilot in command (PIC) to identify the current and most effective app to fly safely and to meet the project's goals.

Recent research supports the effective application of UAS based, RGB imagery and the use of vegetation indexes in plant ecology and habitat assessments (Cruzan et al. 2016; Dell et al. 2019; Wich and Koh 2018). The Visible Atmospherically Resistant Index (VARI) vegetation index is often used with t-c (RGB) imagery, and the Normalized Difference Vegetation Index (NDVI), is commonly used with m-s imagery, like Landsat satellite imagery (Larrinaga and Brotons et al. 2019; Pettorelli et al. 2005). Dell et al. (2019) worked with UAS-acquired, RGB imagery in distinguishing healthy foliage from necrotic using VARI-processed orthomosaics. Other UAS imagery used with "greenness" indices includes works Larrinaga and Bondon (2019) and Zhang et al. (2019). The use and effectiveness of various vegetation indexes has generally originated from their application in agriculture research and crop health assessments (Larrinaga and Bondon 2019; Zhang et al. 2019; McKinnon and Hoff 2017). Laliberte et al. (2011) applied methods derived from crops research. They used m-s WV-2 satellite, and fixed-wing UAS, high-definition imagery to develop a processing workflow to calculate rangeland vegetation classifications. Laliberte et al (2011) determined that the application of multi-scale UAS data and its upscaling was possible.

The evaluation of RGB-based vegetation indices from UAS imagery includes the works of Lussem et al. (2018) and Larringa and Brotons (2019). The value of the VARI is that it reduces atmospheric effects, is applicable for imagery acquired from low-flying UASs in areas of large amounts of bare soil, and correlates better with vegetation fraction than the Green Red Vegetation index (GRVI), also used with RGB data (Larringa and Brotons 2019).

Roosjen et al. (2018) used UAS imagery data to estimate leaf area index and leaf chlorophyll content. A unique aspect to Roosjen et al. (2018) was using multi-angular image data rather than with images taken with the typical nadir (straight down) sensor position. Schneider et al. (2018) compared the use of the NDVI, versus the VARI, with RGB MODIS satellite data to estimate live fuel moisture (Fire Potential Index-FPI) and concluded that the VARI-FPI outperformed the NDVI-FPI for distinguishing between a fire- and no-fire event for historical wildfire data.

The VARI, used for RGB imagery, is not a replacement for the NDVI (which uses a m-s; NIR band) as an indicator of vegetative (crop) health (McKinnon and Hoff 2017; Herrick 2017). The VARI is sometimes called the false or synthetic NDVI, and estimates the fraction of vegetation in an image with low sensitivity to atmospheric effects (which exist in low-altitude UAS flying). The VARI indicates how green plants are, or the "greenness" of the image, and can be used to approximate relative plant health (Herrick 2017; Zhang et al. 2019; McKinnon 2017). This is compared to the NDVI, which is a measure of healthy, green vegetation (Gitelson et al. 2002).

The VARI is interpreted using the same scale as the NDVI, from -0.1 to +0.1. An NDVI score of approximately 0.2 to 0.8 represents green vegetation. Using the VARI, a positive value represents a higher level of "greenness" (vegetation) than a negative value in the image (Agisoft Metashape 2020; ArcGIS 2018). Despite the difference, the VARI is found to be an effective index for measuring and analyzing the level of vegetation (“greenness”) and biomass monitoring in grasslands with the high spatial and temporal resolution of RGB sensors, such as those in MODIS satellite and most UASs (Lussem et al. 2018; Dell et al. 2019; Larrinaga and Brotons 2019; Schneider et al. 2008).

With the increased use of UASs imagery, it is also necessary to develop the capabilities to analyze, geo-rectify, and interpret these images (Lopez and Frohn 2018; Han et al. 2017; Bhandari et al. 2012; DroneZon.com 2018; Calvo 2015). Image analysis tools and software programs for developing interpretive maps and data include Agisoft Metashape (2020; 2019), ArcMap 10.8, DroneZon.com (2018), PIX4D mapper (2018), and Drone Deploy Plant health map, (2018). Example software for converting acquired m-s imagery into vegetation indexes; or processing images with supervised or unsupervised image classification methods include: ArcMap 10.8 (2021); Earth Data Analytics (2018); and Earth Resources Data Analysis System (ERDAS) (2018).

Acquired imagery is first processed with relative efficiency into orthomosaic and digital surface models (DSM) using image processing software such as Agisoft Metashape, ArcMap, or Pix4 D. The resulting orthomosaic can be analyzed using vegetation indices raster equations in Agisoft Metashape (Agisoft Metashape 2019;2020) and unsupervised and/or supervised classification with ArcMap software (ArcGIS 2021). ArcMap unsupervised and supervised image analysis methods are used to classify spectral (pixel) groups. The resulting classification images are used to define site condition (fire footprint post-fire and recovery), and diversity (separate habitat or vegetation types) based on the spectral signatures (see *Methods, UAS Image Processing*).

Lisein et al. (2015) and Zahawi et al. (2015) used UAS drone imagery to process group classification and separation of habitat types. The group classification of RGB, UAS imagery performed by Lisein et al. (2015) examined deciduous tree habitat. Zahawi et al. (2015) classified the recovery of tropical forest habitat. Louargant et al. (2018) used the results of an unsupervised classification process to develop a training sample used in a supervised classification process of m-s images of row crops. Results indicated that combining the classification methods improved weed detection, and Louargant et al. (2018) noted that texture and shape could be detected in the high-resolution imagery and used with the spectral (color) groupings to discriminate vegetation and other classification types.

In summary, the use of imagery for characterizing grassland composition has been identified as a need to conserve and manage these systems (Bond 2016). The UAS platform and high-definition sensor is a highly effective tool for collecting information on grassland systems and species composition at the ground cover level. Technological innovations (reduced size and weight, more-available or interchangeable sensor-types), high image quality, and ease in imagery processing continue to advance the use of the UAS as a tool for ecosystem evaluation (Laliberte et al. 2011). The accessibility of both the UAS platform and processing software has contributed to developing community-based conservation and ecosystem evaluation efforts (Paneque-Galvez et al. 2014; Calvo 2016).

METHODS

Methods used for this research included the 1) collection and processing of a) georeferenced UAS mapped surveys, and b) researcher-developed methods of UAS Low Altitude Quadrat Imagery (LAQI) acquisition and ad hoc under-the-canopy UAS flights; 2) In-field quadrat ground cover abundance estimates; 3) review of supplemental existing Landsat satellite data, historic black and white aerial images of the study site; and the 4) examination of traditional ecological knowledge, and a local community questionnaire.

Study Site

Navy Wells is located at the southwest end of the Atlantic Coastal Ridge near the city of Homestead, FL, close to the ENP Long Pine Key, approximately 4.8 kilometers (km) (three miles[mi]) to the northeast of ENP (Appendix 2; Figure 3). The Navy Wells study site is one of the three largest remaining PR sites in S. FL, and is designated by the State as one of four exemplary S FL PR preserves. It is the largest, intact M-D County PR conservation preserve, with approximately 130 ha (322 ac) of PR habitat consisting of 92 ha (227 ac) county-managed lands, and 38 ha (95 ac) held by the State of FL as part of the FL Keys Aqueduct Authority. The Federal government acquired the property in 1941 to establish the aqueduct. In 1969 it was identified for future acquisition by M-D County in the Open Space and Recreation Master Plan, and acquired in 1977. The preserve was placed in perpetuity as conservation land in 2004 by the County EEL program. Navy Wells has an early history of pine forestry and family settlement with light agriculture since the 1900s.

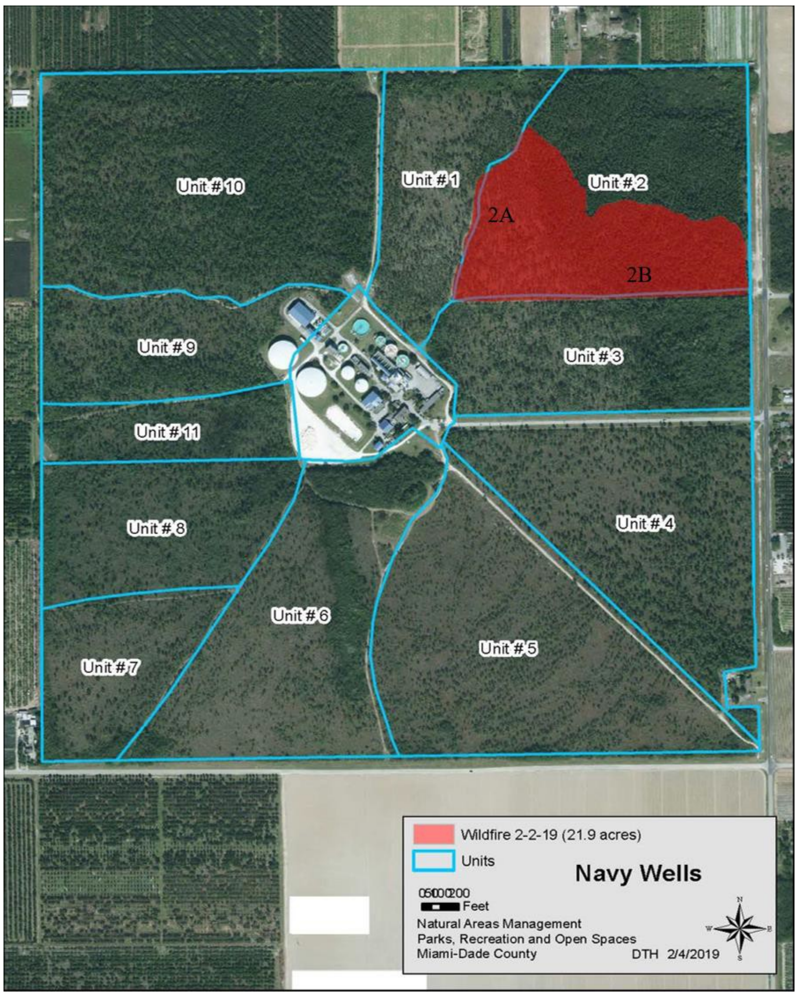


Figure 3. Navy Wells with February 2, 2019 burn footprint 2A and 2B, red polygon. Center Point Coordinates: Latitude: 25° 26’ 18.52” Longitude: 80° 30’ 24.51” (M-D County 2019).

Navy Wells was selected for this research because of the structural and compositional diversity and heterogeneity of the PR habitat present at this preserve. A diverse representation of intact endemic herbaceous, grass, and plant species are also documented and surveyed at this site.

The site has one paved main entrance road. Narrow dirt access roads created during historical forestry and farming extend from the main road and are used today for access during fire and management activities. The Navy Wells PR habitat is identified in units, using the access roads as boundaries (Figure 3). The habitat conditions vary across the units based on their fire history and hardwood thinning management actions; the limestone substrate is present, but broken in many areas from historic farming (raking) practices.

The PR habitat is marked with “conservation area; no entry” signs at the access road entrances. During the 15-month research period (over 100 total hours on-site), there was occasional weekend community recreational ATV use (one-two ATVS at a given time) observed on the access roads. On two occasions, butterfly and bird watchers were observed walking the roads; and no persons or vehicles were ever observed within or traveling through the PR habitat.

S FL is a subtropical system with distinct wet and dry seasons. The average yearly rainfall for Homestead, FL is approximately 147 cm (58 in) (World Climate 2021). From December 2018 to February 2020, Homestead, FL experienced wetter-than-normal conditions during the research period, recording 19.3 cm (7.62 in) above average precipitation during the time period (NOAA NWS, 2021).

On February 2, 2019, a nine ha (22 ac) wildfire (arson) occurred in the Navy Wells Unit 2. The fire footprint is mapped in Figure 3 (M-D County 2019). The entire Unit 2 is approximately 16 ha (40 ac). Because of the fire, the site offered an ideal location to collect data on PR habitat post-fire and compare two adjacent areas with different baseline habitat conditions that had both burned. For the purpose of this research, Unit 2 was referenced as Units 2A (west side) and 2B (south side) (Figure 3). Prior to the fire, Unit 2A was an area of open ground cover (with low density, midstory hardwood overgrowth), and Unit 2B was an area of dense, hardwood overgrowth. The last record of fire on Unit 2 was a November 2001 prescribed burn. Unit 2A had previous reduced hardwood shrub management before the 2001 burn. Unit 2A also consisted of an approximately 400 m^2 (4306 ft^2) depressed area with a thin layer of accumulated organic material and soil overlaying the limestone substrate (further referred to as “Redland soil/grass area”). The fire was a heterogeneous, patchy burn of moderate to light intensity, similar to a prescribed burn for PR. Some fire reached individual pine canopies, but it was not a catastrophic fire. Forestry firefighters got the fire under control, and extinguished it.

UAS imagery

UAS flights consisted of automatic aerial surveys (flight surveys), and manual LAQI, and ad hoc flights. This was one of the first regular surveys to collect UAS imagery for PR habitat. These flights, and the in-field quadrat estimates, were performed on a monthly basis for 13 months from January 2019 to February 2020 (all further work was stopped due to the covid pandemic). The LAQI, ad hoc flights, and in-field estimates, were mostly performed the week prior or the week post the flight surveys. Some exception to this schedule occurred in June, 2021, due to a hurricane preventing work.

Each selected biological indicator for the LAQIs and in-field quadrats estimates were geo-referenced as a center-waypoint (WPT) and marked with a small flag. Each indicator became the center WPT for a LAQI quadrat, and was tracked over the length of the research (Appendix 3). Georeferenced cell photos were also collected for each LAQI quadrat the day of flight. Additional cell photos were collected throughout Navy Wells during the research period. Unless specified, all UAS images and cell photos were produced by the author for this research.

The Primary Investigator (PI) possessed a Federal Aviation Administration (FAA) remote pilot license, and a Department of Interior (DOI) remote pilot certificate, and also acted as the PIC. The PI/PIC developed the project aviation safety plan (PASP) and daily flight plans, and flew as the PIC of the UAS flights (with the exception of four flights flown by another remote pilot, at which time the PI acted as the Visual Observer (VO). The PI completed Basic Wildland Firefighter Training certification in August 2019 (S130/190; L-180), which included content in fire behavior and prescribed fire methods.

UAS Flight Surveys

The automated UAS flight surveys were flown using small UASs, primarily a Mavic 2 Pro, or occasionally the Phantom 4 Pro+ (see Section, *UAS Equipment*), and acquiring t-c, RGB images (Figure 4). The MapPilot app was used for flight planning and

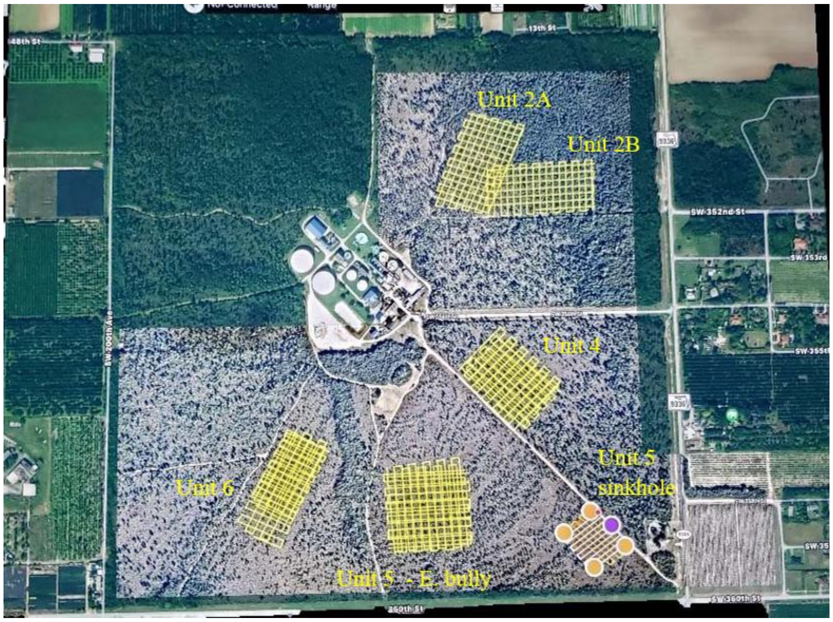


Figure 4. Example automated UAS flight paths in Navy Wells using MapPilot app.

automated flight surveys above-canopy, with the exception of four flights (Navy Wells Units 1 and 3, and Miami Zoo Unit 9, post-fire) in which the Pix4D app was used. These apps worked similarly in the planning process and image acquisition of georeferenced .tiff images. Both apps are user-friendly, reliable, and free or relatively inexpensive. The MapPilot app had a greater capability for pilot-adjusted camera and altitude settings and became the primary method for planning and executing these flights. Another valuable component with the MapPilot app was the automatic return of the UAS to Takeoff (TO) location in case of low battery level or transmission interruption.

An Apple Tablet was linked via cable to the UASs remote controller (RC) and used as the control center for the MapPilot app flights. Update checks to the MapPilot apps, tablet software, and any UAS software and firmware updates were completed prior to each day's flights.

Flights were performed monthly over Navy Wells Unit 2, the site of February 2, 2019 (wildfire) (Figure 3). Planned, automated, grid-patterned flights were flown over Units 2A and 2B monthly for a full yr., beginning on February 16, 2019 and ending on February 2020. Two perpendicular flight paths (plans) were flown over both Unit 2A and Unit 2B at each monthly flight session (Figure 4). These flight paths were saved in MapPilot.

These standardized flight paths were repeatedly used in the monthly flights in order to compare the same flight footprint (image) over time. The first standardized flights over the fire footprint in Units 2A and 2B in February 2019 were duplicated in February 2020, to allow an equivalent comparison of site images one-yr. post-fire. In addition to applying the standardized flight paths over Units 2A and 2B, other flights of different altitudes and flight paths were also flown at times, to acquire a variety of baseline image mosaics. Additional flight surveys were also completed for Navy Wells in units that, a) of documented high endemic plant diversity (Unit 4 and 5-Everglades bully); b) with a large limestone solution hole (Unit 5-solution hole), and c) provided additional PR imagery baseline data (Units 6 and 7). Flights in Unit 4, Unit 5-solution hole, Unit 5-Everglades bully, were flown at least quarterly. The PI name the different Unit 5 flight surveys for this research to discriminate between these areas.

Flights generally occurred between 10 am to 2 pm, within a 2-hour window around solar noon to avoid shadows, and adjusted for safety and weather conditions. The weather was checked regularly before and during each flight (particularly in the summer). All flight altitudes were below 61 m (200 ft). The majority of flights altitudes were planned to fly between 48 to 55 m (157 and 180 ft), to maintain safety and accommodate for visual line of site (VLOS) rules that require the UAS remain in site during flight. One to two VOs were used for each flight. Flight safety briefings were performed before every flight by the PIC with the 2nd pilot, VOs, and any observers that may have been present. A Navy Wells PR (PASP) was developed in alignment with the FWS UAS program and reviewed by M-D County DERM (landowners) (Appendix 4).

The UAS camera was set to nadir (pointing straight down) for all flight surveys. The image capture along the grid flight path was set to an 85% Front Overlap, and an 80% Side Overlap. Both the Mavic and Phantom UAS sensors (cameras) provided t-c, RBG, vHR (3 cm/pixel [0.5 in/pixel]) imagery. This level of image overlap was to assure adequate photo alignment during the processing of the orthomosaic maps (MapPilot 2020; Calvo 2015). The camera was set on automatic or manual settings depending on light conditions at the time. Typical exposure was 1/200, or 1/500, ISO 100/200. The speed of the UAS was automatically set with MapPilot app based on the flight's altitude and amount of image overlap, with the typical flight speed between eight and 13 km per hour (kph) (five and eight mi. per hour [mph]). One advantage of the Pix4D app was its ability to allow the UAS flight speed to be set manually by the PIC.

A single flight survey was flown over Unit 2A in June 2019 with DOI pilots, using the Solo UAS and RedEdge m-s Red, Green, and NIR (RGN) camera. Two experimental flights, one in Unit 2A and one in Unit 2B, were also flown in January 2020 using the Phantom 4 Pro+ UAS, modified with an added MAPIR "Survey 3 Wide" aerial mapping camera equipped with a m-s Orange-Cyan-NIR (OCN) filter. The Survey 3 camera, attached to the Phantom, was set to a 5-second interval image capture and collected images while the Phantom flew an automated MapPilot flight survey. Flight images were acquired simultaneously with the Survey 3 camera as flight images were also acquired with the Phantom's integrated camera. The OCN images were RAW and converted to .jpg on the camera's data card. The RGB, t-c images acquired with the Phantom's camera were downloaded as usual during the MapPilot flight survey. Calibrations for both the m-s RedEdge, and MAPIR OCN cameras were performed prior to flights (MicaSense 2019; MAPIR 2019a).

Products produced from these aerial surveys included individual georeferenced .tiff images, transmitted and downloaded during flight to the MapPilot App folders. The MapPilot app also produced a single excel file of image metadata (speed; altitude) for each flight. The folder of the images and excel file was transferred from the app through email. The Pix4D app provided georeferenced images but did not provide a separate Excel metadata file.

All flights were recorded onto a Flight Log with the following information:

- Date/Time, Location, weather conditions;
- PIC /2nd pilot/VO names (initials),
- UAS platform, Check on Firmware update;
- Flight number of the day; TO and landing time, Altitude flown; Total flight time;
- Battery ID number, Percent battery capacity on TO and Landing;
- RC and Tablet percent capacity on TO and Landing and;
- Comments, notes or issues encountered.

UAS imagery was processed into orthomosaic images and DSMs for further examination and analysis. See Methods Subsection, *UAS Image Processing*.

UAS Low Altitude Quadrat Imagery (LAQI) surveys and ad hoc flights.

The following LAQI and ad hoc flight methods are researcher-developed methods for UAS flights, manually flown under-the-canopy, to collect quadrat and indicator data of the PR understory. The LAQI flights were used to capture individual repeated, overhead quadrat and WPT indicator images. The ad hoc flights were brief flights at low altitude to collect overlapping images processed into small orthomosaic images ("snapshots").

Biological indicators as LAQI center-waypoints. An objective of this research was to examine how the UAS platform could be used to collect and assess habitat health through the identification and tracking of indicators. Repeated under-the-canopy LAQI surveys were flown over the WPT locations in Unit 2A to document the condition of the indicator and surrounding ground layer, and the recovery of the herbaceous ground cover, post-fire. Individual ground cover biological indicators were identified and used as quadrat WPTs for the repeated LAQI surveys. Most of the ground cover indicators (forbs, grasses, and shrubs species) were selected during a March 8, 2019 post-fire field visit with a PR expert, Botanist J. Possley, and M-D County PR Land Manager, S. Thompson. The LAQI (WPT) indicators were selected by the researcher based on the input during this field visit, as well as through the review of existing published and unpublished literature on biological indicators and PR habitat, discussions with species experts (FWS ESA staff; and lepidopterist, M. Salvato), and the IRC PR Plant List online resources

(IRC 2021). Two LAQI quadrats (labeled as LAQI 2QA and 2QB) were initially selected during the first post-fire field visit, February 24, 2019, as trial plots to calculate the quadrat size and standardize the UAS LAQI flight method. The LAQI 2QA and 2QB were retained as quadrat WPT indicators and surveyed throughout the study period. Additional plant species (new growth, blooming, or a first sighting) observed during the research trips were added as indicators and included in the monthly LAQI flight surveys.

The GPS (longitude and latitude) coordinates were recorded for each of the selected LAQI WPT indicators (Appendix 3). The indicator was given a number identification (ID), The ID was written on a 3-inch-wire flag that was placed adjacent to the WPT-indicator and left in place for the duration of the research. A geo-referenced close-up cell photo of each center WPT and a photo of each quadrat (distance photo) were taken when a) an indicator was first identified and flagged, and b) with each LAQI/In-field survey. Sketches and field observations were made for each quadrat during each survey.

Low Altitude Quadrat Imagery (LAQI) Flights. Twenty-five LAQIs (quadrats) were flown on a monthly basis from February 24, 2019 to February 22, 2020 using the LAQI flight collection procedures. The repeated LAQI surveys were used to acquire imagery for tracking each indicator (WPT) and the surrounding plot. A summary of LAQI flight dates is provided in the *Results* Section.

LAQIs were flown once a month, either just prior to or after (by no more than one week) the larger automated flight mapping surveys. The majority of the LAQIS were collected in the morning hours, just before noon to 1 pm to minimize shadow effects, however, some flights were flown outside of the range to test flight conditions and image results in less-than-ideal conditions. The Mavic 2 Pro was primarily used for the LAQI flights. The UAS compass was calibrated on location before each day's flights.

Based on the measurements and calibrations made with the initial LAQI quadrats, it was determined that with the UAS camera 2.5cm (1 in) sensor, a photo taken at the 3.4 m (11 ft) altitude corresponded to a standardized 2.4 m by 3.4 m (11 ft x 8 ft) quadrat. The 2.4 m by 3.4 m (8 ft x 11 ft) quadrat dimension was verified by using a tape measure and measuring and flagging corners around the center-WPT marker, and then flying over the WPT, confirming that the 3.4 m (11 ft) altitude captured a 2.4 m by 3.4 m (8 ft x 11 ft) image size, matching the ground markers. The measurements were confirmed on two different LAQI quadrats. Images taken at this standard 3.4 m (11 ft) altitude were used for LAQI processing (2.4 m by 3.4 m [8 ft x 11 ft] quadrat) (Figure 5). This 11 ft. altitude successfully acquired quality images with minimal-to-no propeller wash influence to the ground below. If propeller wash began to influence an image, primarily if attempting closer below the standard 3.4 m (11 ft) altitude, then the UAS was raised and flown out of the area. For consistency, the 3.4 m (11 ft) above-ground altitude became the standard altitude for the under-the-canopy LAQI and ad hoc flights.

Figure 5. Example LAQI WPT 28; 2.4 x 3.4 m (8 x 11 ft) quadrat at 3.4 m (11 ft) altitude, over WPT indicator; Croton, orange marker flag beside croton. July 6,2019.

The standardized LAQI manual flight procedures were followed for each site visit: Before each flight, the WPT indicator flag was laid flat and adjacent to the indicator species (so the flag number could be read in the image analysis). The UAS would enter the quadrat above or near the 4.6 m (15 ft) altitude to assure that effects from the propellor's actions (prop-wash) would not impact the vegetation. The camera was set to nadir. The UAS was flown over the center quadrat WPT, with the UAS facing in the same direction for each collection period. With the UAS centered above the WPT indicator in a stable hover, LAQI photos were taken from 4.6, 4.0, 3.4, and 3.0 m (15, 13, 11, and 10 ft) altitudes. Two images were captured at the standard 3.4 (11 ft) altitude for redundancy. After images were collected at a LAQI, the UAS was elevated and flown out of that quadrat and to the next LAQI. This process was repeated until all planned LAQI flights had been completed for that day. Efficiency in the flying methods improved, and familiarity increased of the area, so more LAQI flights could be completed in a site single visit. Eventually, all twenty-eight WPTS could be flown in a single field research day. To avoid prop damage to ground vegetation, specific open patch areas were used as TO and landing sites with a small landing pad. The in-field quadrat evaluations, with cell photos, were completed after the LAQI flights that same day.

The resulting LAQI images were single, high-definition .jpg images, downloaded from the UAS data card for analysis and processing (see *Methods*, *UAS Image Processing*). A summary of WPTS and the LAQI flight dates are presented in the results. The LAQI WPT coordinates and date first recorded are provided in Appendix 3.

Ad hoc Flights. Ad hoc imagery acquisition was developed during this research as a means of acquiring under-the-canopy ground, overlapping images that could be aligned into small orthomosaic “snapshots” or “postcard” images for use in examining ground cover diversity. The ad hoc imagery method evolved from simply making use of remaining battery power that the UAS batteries had after the LAQI imagery was collected, but, was too low in power to continue to be used for LAQI flying (field assistant and biologist J. Howe first made use of the low remaining battery power to take photos). Recognizing the high quality of these images, and the information they were capable of providing, a standard method was developed to collect overlapping images for processing orthomosaic images of the ground cover. The geo-referenced images could be aligned and processed into high-definition, small-scale orthomosaic images with adequate image overlap. These snapshot images could be used for studying select areas of the ground cover beyond that of the single WPT LAQIs, and as a close-up subset of the larger flight surveys.

The ad hoc imagery is a set of images flown manually at a consistent altitude and a set “timed image capture,” collected across a selected area of ground cover. The PI devised a standardized method to manually fly the UAS at a 3.4 m (11 ft) altitude in a stop-hover-start fashion, with a nadir camera set to an automatic five-second photo capture. The 3.4 m (11 ft) altitude was used to maintain consistency with the LAQI images and provide the capability for aligning and comparing the ad hoc images with LAQIs.

The UAS pilot manually stops and hovers the UAS for the camera to capture to the image, then flies the UAS a short distance, hovers for image capture, and proceeds in this manner along the flight path, while also making sure to provide adequate overlap in the images. The pilot walks along with the UAS. With trial and error, and experience in the method, the pilot developed a consistent flight process to successfully estimate the distance the UAS could travel between the automatic five-second image capture.

Various adaptations to this method were experimented with such as a) taking a picture every three-seconds, and b) flying steadily (no stop-start hover) with either a timed three-second or five-second automatic image capture. For the pilot to maintain proper and safe perspective on the UASs location in relation to the surrounding vegetation, it was necessary to walk with the UAS. However, in the instance of steady flight (with no stop-hover-start), flying smoothly while walking with the UAS was found difficult on the uneven limestone and for avoiding trampling vegetation. The fly and hover method allowed the pilot time to move along with the UAS safely. Taking a picture every three-seconds assured there would be enough image overlap. However, this method created more images and more overlap than was needed, would not allow the UAS to travel a productive distance between image capture, and resulted in taking too much time and battery power. The manual fly and hover, with an automatic five-second image capture was found to be the most successful in capturing quality, overlapping images in the habitat conditions.

All ad hoc images were captured under the canopy in Unit 2A. A variety of locations were selected for flights in this unit, including areas that represented a mosaic of ground cover diversity, grassy areas, and areas of heavy shrub, palmettos, or exposed limestone. A few experimental ad hoc flights were flown in PR areas (Unit 2B) with heavy shrub overgrowth. The standard 3.4 m (11 ft) altitude was often able to be used to fly over the shrub, but the imagery was often blurred or did not mesh well because of the proximity of the camera to the shrub vegetation below (similar distortion in flying too close to a pine canopy). Flights above 3.4 m (11 ft), but still clear of the shrub canopy, were possible.

The number of images captured per ad hoc varied according to the amount of battery remaining (length of the flight) and manner of flight. Single flights were between a total of 30 to 75 images. The .jpg images were processed into orthomosaic and DSM images for examination and analysis, similar to the automated UAS flight surveys (See *UAS Image Processing*). These smaller flights are more rapidly processed into smaller mosaics than the larger flight surveys, and can be used to identify detailed spectral and textural signatures of the ground cover.

As ground cover vegetation recovered post-fire, or in areas in the site where the limestone was too uneven, a small, elevated platform was used to avoid prop damage to vegetation during the TO and landings for the LAQI and ad hoc flights. The PI manufactured the raised TO/landing platform, using a lightweight sweater dryer rack and piece of particle board secured with plumber ties (Figure 6). A shoulder strap was used to

Figure 6. Solo UAS on raised TO/landing platform

carry it in the field. A small 60 cm (23.5 in) square, 55 cm (21.5 in) high, collapsible (children's) table (not pictured) was also used as a TO and landing platform in tall grasses, as vegetative ground cover density and height increased during the season. Because nearly all of the LAQI and ad hoc flights were flown by the pilot when alone, for safety and to assure pilot awareness during all stages of flight, the TO or landing of the UAS was not performed by-hand (i.e., holding the UAS on TO, and capturing the UAS on landing/shutdown).

UAS basic settings and procedures used for flying under the canopy, at low altitudes, and with low battery levels. All or part of the LAQI and ad hoc flights were commonly flown using reduced battery levels (often below 50%) while flying under a "ceiling" of pine canopy. In this case, the "low battery level" warnings for the UAS were set as low as possible to take the greatest advantage of the available battery power. Flying with reduced battery levels was possible because of the controlled flight environment with the smaller flight routes and low altitudes. Vigilance was used to avoid the automatic Return to Home (RTH), which would cause the UAS to climb automatically before returning to its TO location. The TO and landing (finishing) locations for these flights were planned to the greatest degree possible, prior to flying, and settings were changed to accommodate safe, smooth, and effective flight methods under the canopy. If a low battery warning was reached during a flight, the pilot returned the UAS expeditiously to the original TO location or landed in a clear area near where the flight would finish, and that had been identified in planning. Obstacle avoidance was achieved with the pilot maintaining visibility on the UAS and manually maneuvering around trees or over larger shrubs. Prior to flights, the UAS obstacle avoidance warning settings were turned off. In some cases, this still did not override the front obstacle avoidance which "braked" the UAS when too close to a tree. In this case, the pilot maneuvered the UAS around the trees by rotating the UAS and flying laterally to avoid the front obstacle braking system. Basic UAS settings used when flying under-the-canopy included:

1) Set low battery warning alarm signal to the lowest battery level possible (15%) to take the greatest advantage of the available battery power.

2) Set the automatic Smart RTH for low battery to “off”. And as precaution, check RTH altitude and set as low as possible (A default RTH can be over 50 m). This will activate with a critical low battery. Be prepared for immediate landing or a manual override.

3) Do not let battery reach the “critical low battery” warning level.

4) Change RTH setting for lost remote control signal loss to “hover”.

5) Set obstacle avoidance “Off”.

Additional UAS setting changes are possible for managing UAS speed, sensitivity, and maneuverability under conditions like the open pine canopies or similar habitats. Further information can be found online by searching for the use of small UAS indoors, or for search and rescue.

UAS Equipment

Small UASs are defined by the FAA and discriminated from the larger (often military and/or professional) UAS platforms, as those UASs that weight less than 25 kg. (55 lbs.). Small UAS platforms were used for all UAS imagery acquisition in this study; for this study, “UAS” refers to small UAS platforms.

The UASs used were the DJI: 1) Mavic 2 Pro (Mavic) and 2) Phantom 4 Pro+ (Phantom). The specifications are provided below. The Mavic was used as the primary platform. The Phantom was also used for video and was adapted for the acquisition of m-s imagery. Both UASs came equipped with a t-c (RGB) 1 in. sensor with a 20 mega-pixel spectral resolution. A 3DR Solo model UAS was occasionally used for video (see specifications below). The 3-band, RGB sensor has a 0 to 25, 24-bit color (8 bits for each color; t-c); 256 possible pixel values.

Aircraft

DJI Mavic 2 Pro: Information for this platform is available at https://www.dji.com/mavic. An advantage of the Mavic for this study was its small size and portability for field work (Figure 7). Figure 7 provides the Mavic 2 Pro platform specifications. The Mavic flight equipment (flight deck) used in this research is shown in Figure 8. The UAS' maneuverability and stability in flight was an asset for under-the-canopy flight (Figure 9).

Mavic 2 Pro Specifications:
Folded size: H83mm x W83mm x L198mm (3.2 x 3.2 x 7.8 in)
Diagonal Size (Propellers Excluded): 335 mm (13 in)
Weight (Battery & Propellers Included): 1.62 lbs. (734 g) (excluding gimbal cover);
1.64 lbs. (743 g) (including gimbal cover).
Max. flight time: 27 minutes (no wind at a consistent 25 kph (15.5 mph).
Max. hovering time: 24 minutes (no wind).
Overall flight time: 21 minutes (In normal flight, 15% remaining battery level).

Figure 7. Mavic 2 Pro.

Figure 8. Mavic Pro 2, RC, and tablet (flight screen) used for this research.

Figure 9. Mavic in flight under the canopy.

DJI Phantom 4 Pro+: Information on this platform is available at: https://www.dji.com/phantom-4-pro. Figure 10 provides specifications for the Phantom platform.

Two flight surveys were collected in two different sections of Unit 5 (Table 3) using the Phantom (Figure 11). This UAS was equipped at the time of purchase with a RC with an integrated flight screen. While providing excellent visibility and ease of use (no tablet or phone is needed), the integrated flight screen does not allow for outside apps, such as MapPilot, to be downloaded and used with the model. To adapt this UAS

Phantom 4 Specifications: Weight (Battery and propellers included): 1388 g Maximum flight time: Approximately 30 minutes Vision System: Forward vision system; backward vision system; downward vision system. Obstacle avoidance: Front and rear obstacle avoidance; left and right infrared obstacle avoidance. Camera Sensor: 1" CMOS effective pixels: 20 M. Maximum video recording resolution: 4K 60P. Maximum transmission distance: FCC: 4.3 mi Operating Frequency: 2.4 GHz/5.8 GHz transmission

Figure 10. Phantom 4 specifications.

for automated flight surveys with the MapPilot app, a compatible Phantom RC without an integrated screen (Model 300L) was connected by cable to an Apple Tablet. Through the UAS's DJIGO4 App UAS settings, the high-definition wireless transmission frequency was changed from the typically used 2.8 mHz band to the 5.8mHz band, and the RC was able to be linked to the UAS as the primary RC to allow use of the MapPilot app on the Tablet (Figure 11; RC on right in image). Because of its ease of flight with the integrated flight screen and larger, stable size, the PIC (Figure 12) used the Phantom with beginner remote pilots (including student interns).

Figure 11. Phantom UAS and RCs.

Figure 12. PIC setting up the Phantom.

Use of MAPIR OCN Survey 3 camera used on Phantom. Set-up instructions and user guidelines for the MAPIR survey 3W camera, including attaching the camera and GPS frame (Figure 13), camera calibration, and correct settings for image capture, are provided online at the MAPIR website (MAPIR 2019a; 2019b; 2020). The MAPIR Survey 3 Wide camera (5.5 cm/pixel; 87° Field of View [FOV]), was used to collect OCN m-s images. The camera's FOV is similar to the other DJI cameras on the UASs used in this research.

Figure 13. Phantom with MAPIR camera and GPS unit on mounting frame; Right: closeup of MAPIR GPS unit.

3DR Solo: The 3DR platform is no longer supported by the manufacturers. Information was available online at https://3dr.com/solo-drone/. The 3DR solo UAS is shown in Figure 14; Box 1 provides specifications for the Solo. This drone is now obsolete and no longer provided with firmware updates. For this research, it was used for acquiring video.

Digital Trends

Box 1 Solo Specifications:
Solo includes a GoPro® Hero camera with fixed camera mount and HDMI cable (HDMI cable connects to the camera to output video during flight.)
Height: 10.2”
Motor-to-motor: 18.1”
Estimated flight time: up to 25 minutes.
Range: 0.5 mi (0.8 km) depending on transmission strength.

(Solo3DR User’s Manual)

Figure 14. 3DR Solo. Box 1 Specifications.

Additional equipment used in the research includes:

- Handheld GPS Unit Garmin GPS Map 73.
- ICOM VHFIC-A24 Handheld Air Band Transceiver (to monitor surrounding air traffic).
- Small 3" field flags.
- UAS TO/landing pads.
- Tape measure.
- Geo-referenced cell phone camera.
- Software Apps: DJI GO4, MapPilot, Pix4D, MAPIR camera, Garmin MapSource.

The UAS imagery data records (types of flight; flight dates) and image processing were tracked in an Excel spreadsheet (Figure 15):

UAS Imagery Records for Surveys, LAQIs, Adhocs, Cell Photos								
UAS Flight Survey Number	Navy Wells Unit	MapPilot Survey Date	LAQIs Date	Ad hoc# /Date	Cell Photos (Y/N)	Notes	Ortho/ DSM run (Y/N)	VARI run (Y/N)

Figure 15. Data log recorded for UAS flight surveys.

UAS Image Processing

The acquired .jpg images were transferred from the UAS data card after each flight. MapPilot flight images were stored automatically during flight in a MapPilot file and these files were later transferred via email to a computer for processing. The UAS RGB and m-s imagery was processed and analyzed with Agisoft Metashape Professional

v. 1.6.3(Agisoft) software (Agisoft Metashape 2020; 2019), and ArcMap 10.6.1 and 10.8. Landsat and additional existing historic imagery were processed and analyzed with ArcMap 10.8. Maps were produced in ArcMap. Photoshop was used for finishing images. Google Earth was used to illustrate and map GPS and plant point-data and to view overlays of UAS orthomosaic images at the site location. The vHR UAS imagery was used to distinguish and evaluate vegetation and substrate's spectral, textural, and temporal characteristics in the PR habitat.

Orthomosaic images and DSMs were produced in Agisoft using the RGB UAS flight survey and ad hoc imagery, and m-s flight imagery. Following the Agisoft workflow protocol (Agisoft Metashape 2020; 2019), a set of single geo-referenced flight images (approximately 200-250 images) was added to Agisoft, aligned, and processed into the orthomosaic and DSM products. The resulting images were exported and saved as .tiff and .kml files. Vegetation indexes used to examine vegetation's "greenness" and health include VARI with RGB images and NDVI with m-s images. The VARI was calculated in Agisoft using RGB orthomosaic images developed from the UAS flights (Dell et al. 2019; Herrick 2017). An NDVI index was calculated for the m-s orthomosaic images using ArcMap 10.8 (ArcGIS 2018).

ArcGIS supervised and unsupervised image classification. ArcGIS ISO (isodata) Cluster Unsupervised and Interactive Supervised image classifications were processed with the ArcMap 10.8 workflow (Figure 16) using the resulting orthomosaic images processed from the UAS flight surveys and ad hoc flights, and adapting methods from Cruzan et al. (2016) and Dell et al. (2019). Supervised and unsupervised image classifications were also processed with single LAQI .jpg images using the same methods.

The supervised and unsupervised image classification tools were accessed via the ArcMap Image Classification toolbar. The ISO unsupervised classification tool was also accessible through the ArcMap Toolbox, Spatial Analysis Tools, Multivariate Analysis (Figure 17).

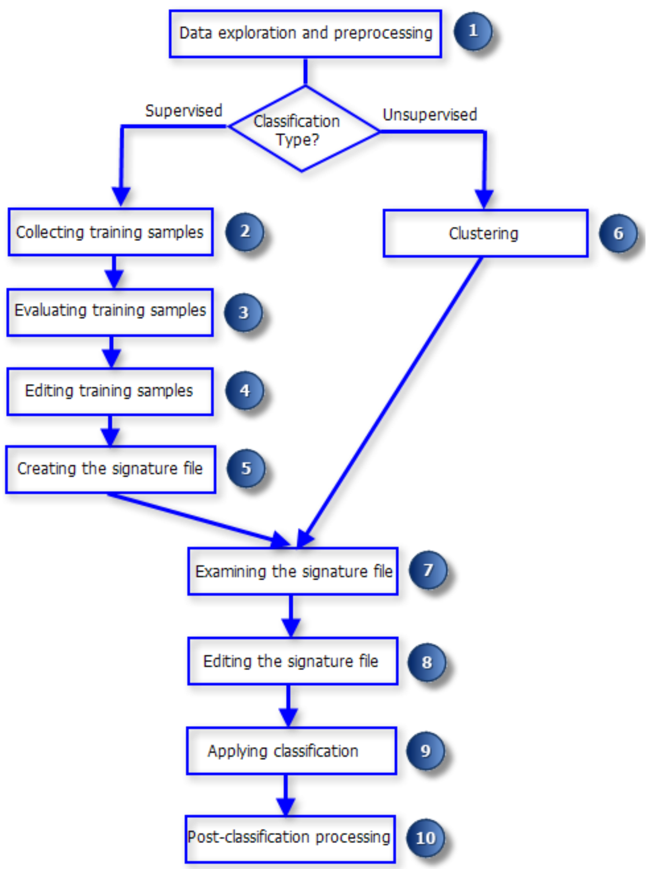


Figure 16. ArcMap image classification workflow (ArcGIS 2021).

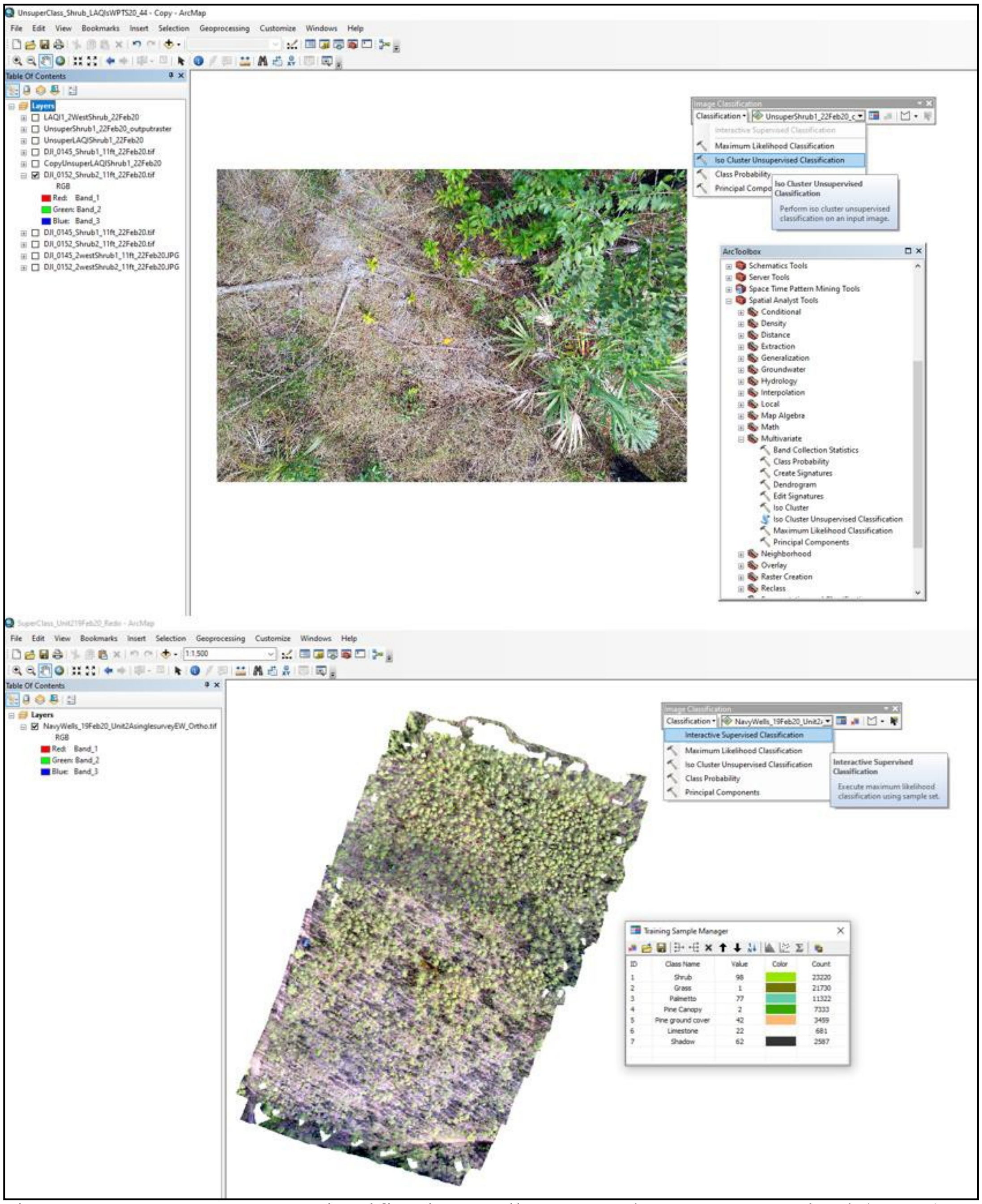


Figure 17. ArcMap Image Classification toolbar. ISO cluster unsupervised (upper) and supervised classification with training sample manager (lower).

Raster group classifications (classes or types) were automatically produced using the unsupervised image classification method following the protocol recommended in ArcMap (ArcGIS 2021), in which the number of classes in the "Spatial Analysis" step are to be set at ten times the number of spectral bands. Using the 3-band (RGB) imagery, the setting for number of classes was thirty. The original output raster results in a stretched color ramp, so the Symbology setting (in Layer Properties) was changed to "Unique Values" to reveal each class (Figure 18).

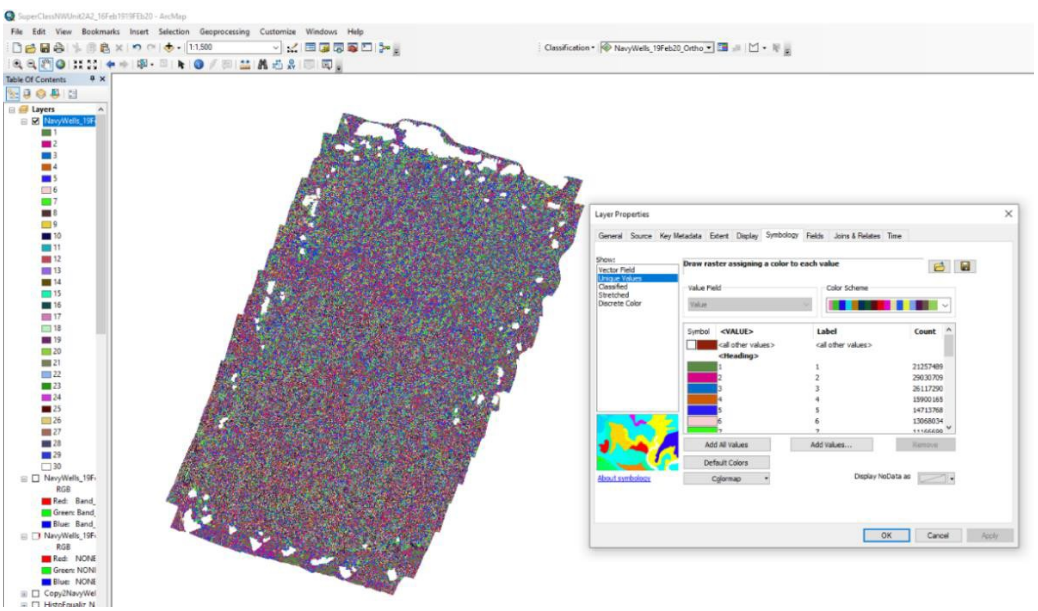


Figure 18. Original unsupervised raster symbology changed to Unique Values.

The habitat types of the output classes were identified using a trial-and-error method and use of the "swipe" tool for comparing the raster classes to the underlying t-c image. Each class was identified with a habitat type, and given a color representative of that type (i.e., classes that represent vegetation are given a green color; limestone classes were given a white color). The greatest number of unique classes or habitat variations wase retained as possible in the process. The raster reclassification process (Spatial Analysis; reclass; reclassify) was used to merge the similarly-colored (valued) classes (Figure 19), and the classes were labeled by classification (habitat) type. The resulting raster was converted to a polygon shape file.

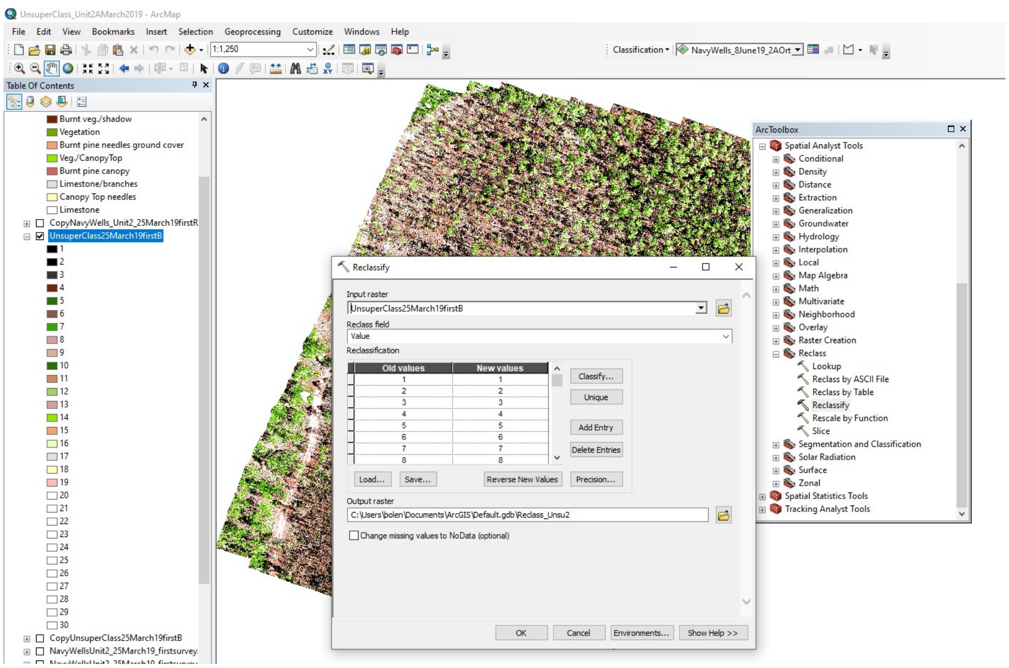


Figure 19. Unsupervised classification. Raster reclassification.

Using the supervised classification method, training samples were produced manually to develop the raster group types (Figure 17, lower). In the development of the training sample group types, the t-c image was used to individually select polygons of distinct groups or classes from the image (for example, dark green grasses, bright green shrub, or white limestone). Example polygons made during training sample development of a UAS image are shown in Figure 20.

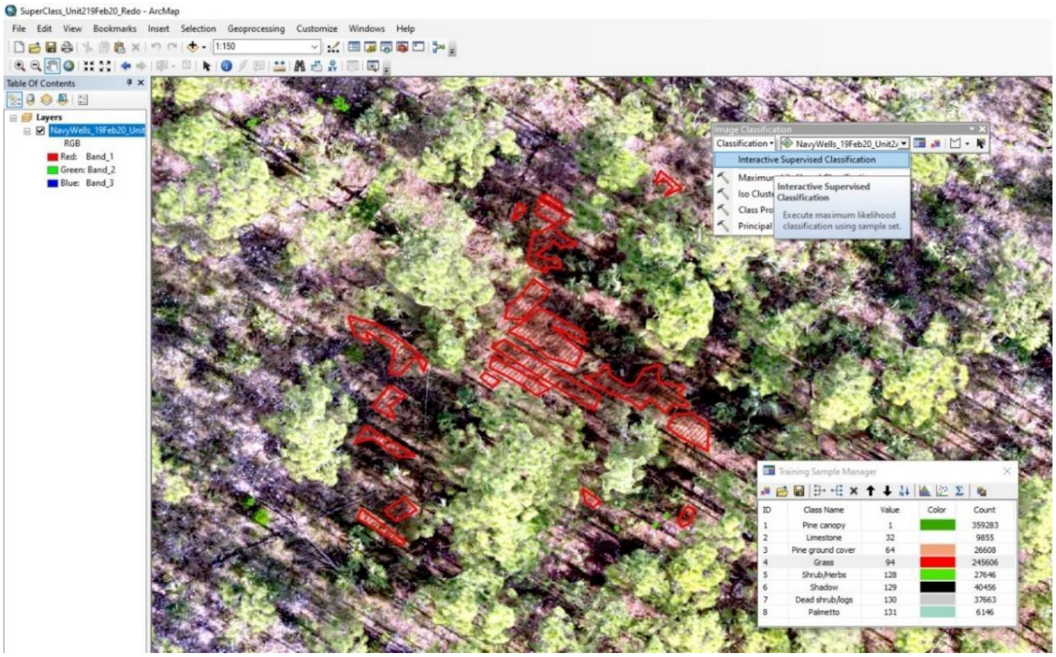


Figure 20. Polygons in development of supervised training sample group classification.

Field verification and close-up LAQI imagery were also used as resources for identifying distinct group types. The selected polygons of the same color (such as the dark green) were then merged in the training sample process to produce a specific group type (such as, canopy). Once all group types were identified, the supervised image classification was run. Training samples were corrected and modified as needed to create the most accurate group types (legend). For further details on the development of group types and training samples using the acquired UAS imagery, see *Results, Processed UAS imagery, Unsupervised and Supervised Image Classification.*

The image classification process was performed by careful selection and separation of the groups. These resulting (supervised and unsupervised) classification rasters were used to identify and examine the main vegetation classifications and diversity (image mosaic), and their separate spectral classes. This study aimed to identify to the greatest extent possible, the variation (diversity) in the spectral signatures (different vegetation types of pine, shrub, palm, and ground cover). This included the identification of limestone substrate, litter layer, and if present, any exposed soil. The typical use of this classification image analysis method is to group or merge similar pixels (spectral colors), rather than split or retain a separation among the different pixel colors. Instead, during the "group type" classification process, as much of the image's pixel discrimination was retained as possible to maintain a (mosaic) picture of the habitat diversity.

Supervised classification histograms and scatter plot diagrams (graphs) were also processed with the Training Sample Manager "Show Statistics" evaluation tool, from the resulting raster images, including LAQI images, to illustrate the degree of class type separation; an example is provided in Figure 21. These graphic results were able to be captured in ArcMap using "print screen". The three separate scatterplots or histograms per graph are automatically processed and represent the pixel signatures for Band 1, 2, and 3 (RGB); specific class types may result in better separation in one band more than another. The resulting rasters were developed into maps using ArcMap. Their legends represent the group classifications (types) identified in the image classification process.

VARI calculations with RGB imagery. The resultant orthomosaic images were processed with the Agisoft VARI raster transform function to calculate the VARI equation ([Green – Red]/ [Green + Red – Blue]; [Band 2 - Band 1]/ [Band 2 + Band 1 - Band 3]). The VARI values were calculated using the a) Automatic -1.0 to +1.0 (Auto),

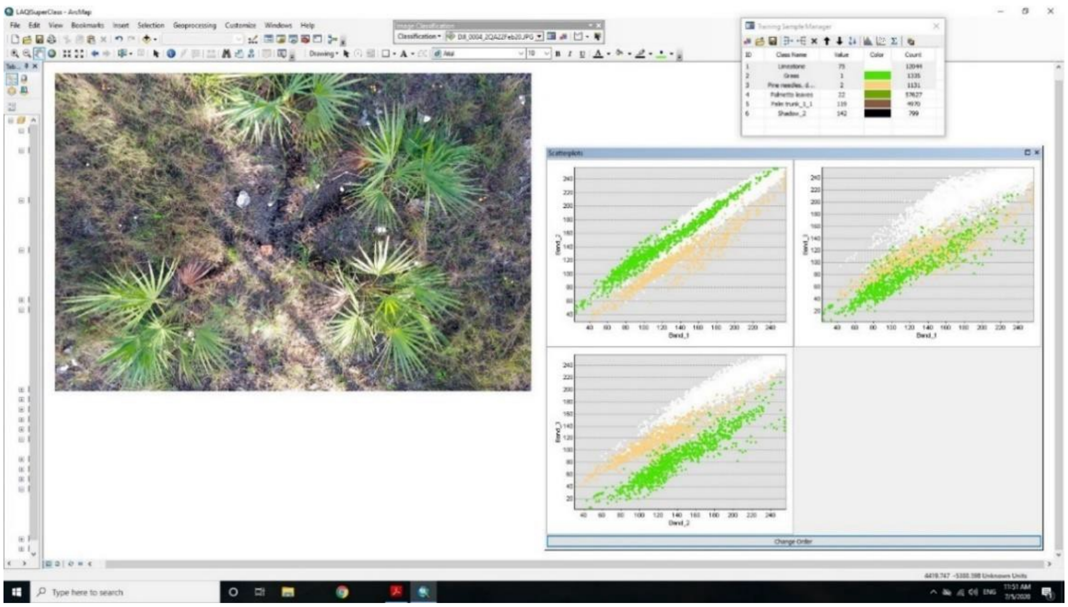


Figure 21. Example scatter plot spectral separation of single LAQI image supervised classification with training sample.

b) +- 0.1, and c) +- 0.3 index ranges (Dell et al. 2019). Different index ranges were used in order to develop images with varying spectral results and to capture the most distinct separation between vegetation classification and other image features for analysis. Each of the Auto, +- 0.1, and +- 0.3 resulting images were processed in both the NDVI and Heat color palettes and saved as .tiff and .kml formats. A variety of indexes and palettes were used to develop variations of an image that could result in either particular highlighting features in the image or increase contrast and distinctions between classes or spectral variations within the image. Based on the calculated index range and palette used in the VARI raster calculator for a specific orthomosaic, specific vegetation classifications could be distinctly separated and highlighted in the resulting image. Figure 22 provides an example of the heat palette in an Agisoft VARI raster calculator, with the range automatically processed, for a January 17, 2019 Navy Wells Unit 4 survey.

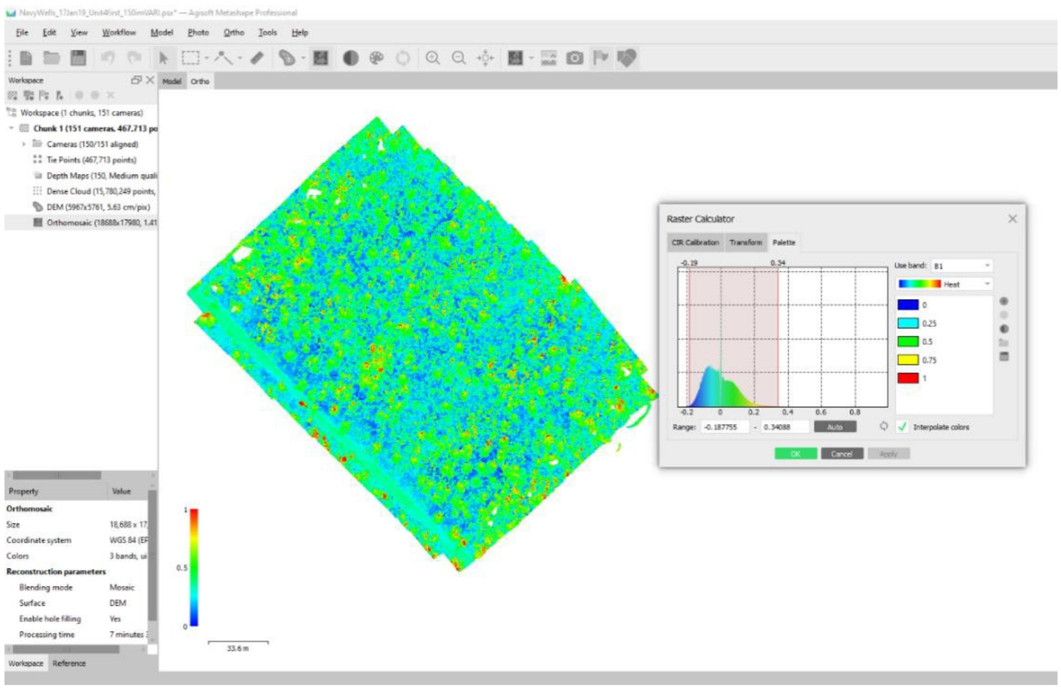


Figure 22. Example Agisoft heat palette used for AUTO VARI raster calculator in a Navy Wells Unit 4 January 17, 2019 UAS survey.

LAQIs

In addition to the supervised and unsupervised image classification, methods used in LAQI image processing and analysis included: a) single image photo interpretation for species indicators; b) temporal, time-series comparison of monthly LAQI WPT images; and c) comparisons with in-field ground cover classification. With the in-field and LAQI comparisons, individuals familiar with the PR habitat were requested to evaluate up to three LAQI images each, and complete a percent abundance estimate using the same worksheet and method used for the in-field quadrat assessments (See Methods Section, *In-field quadrat assessments*, Figure 23). These results were compared to the results of the in-field quadrat assessment for the same LAQI quadrat.

Images acquired with OCN filter

The use of the m-s OCN filter was an exploratory exercise (experimental trial use) to examine the effectiveness of these bands to discriminate between higher vegetation and the ground cover layer, and for comparison with the m-s RGN sensor bands typically used for vegetation indexes. Refer to the *UAS Equipment* Section for methods in securing the Survey 3 Wide camera on the Phantom.

The MAPIR OCN filter is most commonly advertised for use with single-crop agriculture to discriminate the crop vegetation from smaller, more sparse vegetation and the soil layer. The use of the OCN in the natural, more diverse vegetative habitat was for trial; to provide a different spectral image of the habitat than the m-s RGN. The OCN reduces soil "noise" to "orange" which provides for a more, clear transition between red (orange) and green (cyan) pixels.

The OCN filter captures Orange, Cyan, and the 808nm NIR band as compared to the typical Red, Green, and 850 nm NIR bands used for vegetation surveys. The red band is replaced with orange, the green band is replaced with cyan (blue-green), and the 850 nm NIR is replaced with an 808 nm NIR. The slightly wider bands are used to provide greater contrast between the green vegetation and soil (ground layer). The OCN filter reduces soil noise so green vegetation can more obviously be discriminated in the image.

With the OCN filter, areas of darker green vegetation are more reflective to NIR (and more representative of healthier vegetation) compared to a RGN image in which the dark pixels more likely represent shaded vegetation (MAPIR 2020). The OCN is designed to allow more defined capture of smaller vegetation, blurred using the RGN bands (MAPIR 2020). And what is normally seen as a red and red/yellow soil layer with the RGN bands, is seen as aqua-green in the OCN bands.

After flights, the .jpg images collected by the Survey 3W camera were downloaded from the camera's data card to a computer and processed into orthomosaic and DSM images in the Agisoft software. The MAPIR website provides specific stepwise instructions used for processing the m-s OCN images. Agisoft "Calibration" settings used for the Survey 3W camera were: Pixel size: 0.00155 x 0.00155 mm; and Focal Length: 3.37 mm. Per MAPIR instructions, the "Fixed" Parameters was set to "All"; and the "Generic Preselection" was turned "off" in the "Align Photos" step. (MAPIR 2020).

The NDVI index was used for the OCN orthomosaic with the same methods used in processing the m-s RGN images. In Agisoft, the NDVI raster calculator replaces the RGN bands with OCN bands, respectively, in the NDVI equation (B3-B1/B3+B1). Therefore, the NDVI equation run with the OCN filter is: NIR - Orange/NIR + Orange. The same NDVI +-0.1 index range (with lower values blue; less green vegetation and higher positive values toward healthy, green photosynthesizing vegetation) is used.

The MAPIR m-s OCN filter cannot be compared equally to a true m-s RGN single sensor, because a single sensor still produces some overlap in transmission bands compared to the resulting 3 separate bands from the OCN filter. That is, the NDVI range calculated from OCN flight images cannot be compared equivalently to the range of values from a m-s RGN NDVI calculation. It is necessary to use the NDVI scale values from the OCN bands only against other images collected with that same filter.

The NDVI index is used with the OCN filter to contrast "healthy" (green vegetation) to "unhealthy", or "not so healthy" (green vegetation) (MAPIR, June 29, 2020 OCN compared to RGN). However, the use of the OCN was included in the research for experimental trial for discriminating ground cover in a natural, open-canopy habitat. Using the existing knowledge of the PR land cover and vegetation classifications (pine, shrub, limestone, ground cover), the results are to be used to test a new method and build baseline imagery for the interpretation of OCN bands for the study of natural vegetation.

In-Field Quadrat Assessments

In-field quadrat (plot) assessments were performed monthly on the LAQI quadrats after the LAQI flights of that day were completed. The purpose of field verification was to 1) document the estimated percent abundance of ground cover types in the LAQI quadrats, 2) assist with a blind "proof of concept" exercise comparing in-field assessments results with the results of assessments completed of the same quadrat using LAQI images (see Section, *LAQI image processing*), and 3) test the use of the LAQI imagery and field verification assessments as complementary assessment tools.

The estimated percent abundance of ground cover types was measured in the assessment using a "LAQI in-field quadrat assessment worksheet" developed for this research (Figure 23). The worksheet was modified from Richardson et al. (2013) and Taft

LAQI Field Assessment Worksheet	
Ground cover type	**Estimated percent abundance**
Pine tree (s) – visible trunk/roots	
Limestone - exposed	
Limestone/mix with pine needles (needles/with visible limestone)	
Pine needles	
Grasses (make note dead vegetation on grasses and shrubs but not loose on ground)	
Herbaceous ground cover (forbs)	
Mix of grasses and plants (forbs)	
Palmettos	
Ferns	
Shrubs (woody)	
Dead logs, branches	
Burnt ground (charcoal)	
Burn pine needles	
Burned logs, branches	
Estimated Percent Abundance Ranges: 0-1% 1-5% 5-25% 25-50% 50-75% 75-95% 95-100%	

Figure 23. In-Field Quadrat Assessment Worksheet.

LAQI Field Assessment Worksheet

WPT ____________________ Date____________________ Photos taken: ____close ____distant
(check completed)

Sketch

LAQI Assessment Page 2 (back of field assessment form):

Guide:

Pine tree (s);
Limestone;
Limestone/mix with pine needles (needles/with visible limestone);
Pine needles;
Grasses (make note dead vegetation on grasses and shrubs but not loose on ground detritus);
Forbs (herbaceous ground cover);
Palmettos, ferns
Woody shrubs;
Dead logs, branches.

For each plot:
Provide estimated percent relative abundance of each class to 100% total:
Document <5%; and use 5% to 10% range.
For example:
70% limestone;
10% shrubs;
5% grasses;
5-10% palmettos

Make note and add to sketch the unique or large items: Single live pine trunk. Dead log; blooming plant; groupings of palmettos, ferns, or limestone (to use for reviewing and analyzing against the LAQI spectral image).

Figure 23. continued. Page 2; In-Field Quadrat Assessment Worksheet.

et al. (1995). Richardson et al. (2013) used vegetation indexes for measuring relative abundance of coastal scrub habitat ground cover types, similar to those in PR habitat (open patchy spaces, grasses, herbaceous [non-woody] plants, shrubs [woody vegetation], and litter/detritus).

The assessor used a standardized method when performing the assessment by always facing and assessing the quadrat from the same cardinal direction as the UAS camera faced when capturing the LAQIs. The purpose of this was to have a comparable perspective between the LAQI images and the in-field evaluation and sketch. Each quadrat assessment was limited to no more than 15 minutes at a quadrat before moving on to the next. The condition of the center-WPT indicator was also noted during the assessment. Sketches were made of each quadrat, and other observations (recent rainfall, wet-dry ground layer condition, and insect use) were recorded. A geo-referenced (close-up) photo of the quadrat's center WPT (biological indicator), and a full-photo of each quadrat were taken during the field survey. The in-field worksheet data was transferred to an Excel System Evaluation Workbook (SEW) (See Section *SEW*).

Supplemental Imagery Data and Processing

Existing remotely-sensed data was used as supplemental information to evaluate site changes and for providing a historic visual perspective on site-condition. Resources were searched for images that were available at no cost and able to be directly downloaded. Online sites used to acquire or view supplemental, remote imagery data included: USGS EarthExplorer (USGS 2020); M-D County GIS Portal (M-D County 2020); FWC Florida Fire Occurrence Dataset (Landsat imagery) (FWC 2021); ENP Service (USGS 2004); FDOT (2020); and Google Earth. The Digital Globe website was used to preview larger satellite images for cloud cover and site clarity prior to downloading from EarthExplorer (Digital Globe 2020).

Imagery at the site-, landscape-, and regional-scale was selected to illustrate a) current condition, b) habitat or land-use change over time, c) specific events, such as hurricanes, drought, and fire, or d) plant species distribution.

Numerous Landsat satellite 8 OLI and Landsat 7 ETM+ images of S FL, acquired between 2017 to 2020 with a flight path over the Navy Wells site were reviewed to locate those with low cloud cover and an intact view of the Navy Wells site. Images from both wet and dry season months were included in the search. Selected imagery was downloaded, (extracted) and added to Arc Map for review and processing of the NDVI vegetation index. Landsat images were also clipped to create a specific image for the Navy Wells study site. The resulting images were cropped (finished) using Photoshop Editor, and saved as .tiff and .jpg files for use inserting into the documents.

Historical, archived black-and-white images were obtained from USGS EarthExplorer with thorough searches of the following imagery libraries available on the site: single aerial frames; aerial photo mosaics; high-resolution orthomosaics; and NAIP (National Agricultural Imagery Program). The location's key search words included "Navy Wells Pineland Preserve" and "Homestead, Florida". All available yrs. were searched (no time frame was entered in the search). Resulting imagery was reviewed prior to downloading. Images from 1950, 1952, 1964, 1969 - 1971, 1979, and 1987 were selected and downloaded for use in this study.

M-D County aerial surveys were downloaded from the County's GIS portal of available images dating from 1999 to 2019. This time series set of images were reviewed online for major events and the overall condition of the Navy Wells Preserve. County aerial images from 2006, 2007, 2015, and 2019 were used in this study. Depending on the flight path, an intact image of Navy Wells would consist of between two to 16 grid raster files (flight paths over the site). The individual grid images for a single, full-view of the preserve were downloaded as separate files, and mosaicked (merged) into a single Navy Wells image using ArcMap.

Google Earth software was used to overlay rare plant survey point data (FTG 2017) with UAS map survey imagery. Google Earth was also used to plot the GPS locations for the LAQI quadrats and in displaying images of earlier flights for use as reference information during field work. A photo log of selected, supplemental cell photos taken at Navy Wells during the research period was developed in Photoshop.

Local Species Experts and Indigenous Knowledge

A synthesis approach was used with the extensive, unpublished and published PR literature to examine habitat trends, identify indicators, and to support current research results and observations. Additional information in the evaluation of PR was pursued through community resources, input from PR restoration and fire experts, and species experts. The researcher reached out to environmental contacts of the Seminole and Miccosukee Tribes. A community Traditional Ecological Knowledge (TEK) questionnaire or in-person interview was provided to those community experts with knowledge or experience with the PR habitat. The questionnaire focused on obtaining personal perspectives and opinions about the habitat and its management (Figure 24). Questionnaires were emailed with an introductory letter requesting the

<u>Ecological Knowledge Questions:</u>

Hello. The following questions are designed to capture local knowledge and understanding, to be informal, and used in addition to published research. The questions are being provided to local community members, researchers, and land managers that have association with the pine rockland system. This valuable community-information is to be used cumulatively, with recently collected and existing data, research, and published literature, to holistically examine and assist in answering the question of "What is 'healthy' pine rockland?". These questions are also one step in describing establishing an approach to assess healthy indicators and status of other under-studied and/or endangered habitats. These questions are included as part of my December 2018 PhD dissertation research, "Ecosystem Condition Evaluation Process: Above and beyond the complex, critically-endangered pine rockland ecosystem", George Mason University, Environmental Science and Policy.

Instructions: Please answer these questions as if you are being personally interviewed. Please provide brief answers but long enough to feel you have provided the answer you want. Answer the questions based on your own expertise, background, and understanding. Do not do further research or consult with others as you complete these questions. Your answers are to reflect your own professional, personal, and/or traditional knowledge of pine rockland. Please answer each question in how you interpret that question. There are no right or wrong answers. Again, these questions are meant to be answered impromptu; I am interested in your perspective, and opinion. Thank you. Note: Your name and identity will remain confidential and will not be shared or included in the results.

1. What makes Pine Rockland, pine rockland?
2. Describe what is "effective or good" fire for pine rockland . How much of local knowledge, experience, and scientific research or data contributes to your answer/opinion to this question?
3. Do you have any information to share on the role of fire historically in this area?
4. Do you have any stories or knowledge on unique species and their functions in PR? For example, an interaction of one or more species, or a particular use of a species?
5. Please provide one to three examples (indicators, measures) of what "healthy" PR is (such as like human – use of pulse, HR, body temp. to identify health).
6. Does an umbrella species (or species-suite) exist for pine rockland? Such as, if that species (or species-suite) is "taken care of", then PR is "taken care of"?

Please provide a brief 1-2 sentence description about yourself in terms of the local community, conservation, or your environmental role or job position:

Figure 24. Community TEK questionnaire.

the individual's participation. In some instances, the researcher made a preliminary introductory phone call to the person.

Traditional knowledge and artifact history of the early indigenous Miccosukee and Seminole Tribe communities was examined from available private or academic natural history collections and archives. Online research was made to review and explore the historical use or expression of the S FL pineland habitat. The search sites used for this exercise are provided in the *Results*, *Traditional Ecological Knowledge*. Archived photos of artifacts and tools used by early communities in S FL pinelands were examined as anecdotal information on the role of fire, lightning, or PR species in everyday life. For example, any tools that may have been used to work with fire (such as forms of shovels, rakes, fire brooms, or mats commonly used in today's prescribed burns). Images on early clothing and pottery were reviewed for forms of art that may have depicted fire, lightning, or specific endemic pineland species.

In addition, the PI attended the week-long virtual PR Working Group Annual Workshop in October 2020. In this workshop, the global PR community from S FL, Florida, Abaco Island, Grand Bahamas, and Turks and Caicos, participate and report on current research and management activities of the few and precious preserves that constitute the entire global PR ecosystem.

System Evaluation Workbook Prototype

A SEW was used to document and link to all sources and products resulting from the research assessment. The SEW is a prototype for planning, recording, and reporting a system evaluation. A generalized summary of the iterative process is diagramed in Figure 25.

The intent of the prototype workbook is to also catalog all components of habitat assessment and be a repository for this information. An ultimate goal is to develop a standardized and repeatable reporting process, such as an Ecosystem Evaluation Report (EER), that is transferrable to other locations of the same habitat, such as for the global PR ecosystem. The SEW is also meant to be a guide for "thinking out" the evaluation process and developing the plan for the incorporation of multiple data types and sources.

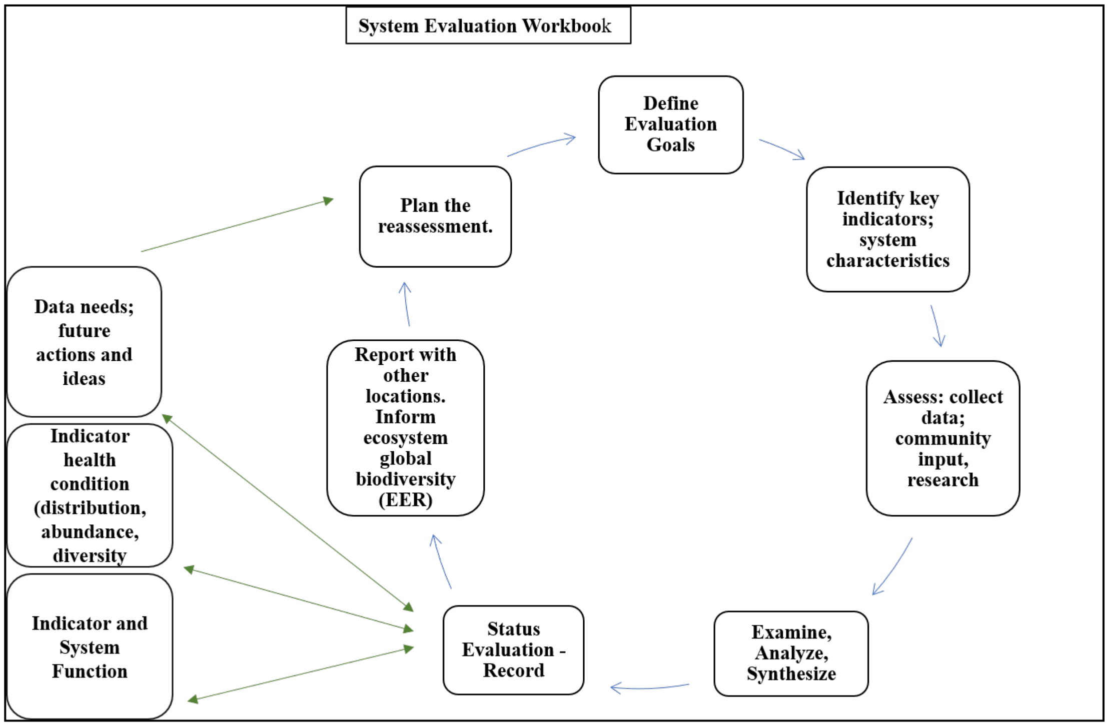


Figure 25. SEW Prototype Process.

RESULTS

UAS Flight surveys

A total 62 flight surveys (above the canopy) were flown within nine units of Navy Wells during the study period (January 17, 2019 to February 22, 2020) (Table 1). Twenty-five and 15 monthly flights were flown in Unit 2A and Unit 2B, respectively beginning on February 16, 2019, over the February 5, 2019 fire footprint. Monthly to quarterly flights were flown in Navy Wells Units 4 and 5-solution hole, with additional flights flown in Navy Wells Units 1, 3, 5-Everglade's bully, 5-FL brickell-bush, and 6. Within a separate PR preserve at Miami Zoo, two pre-prescribed burn flights were flown on November 8, 2019; one flight each in Unit 9 and Unit 10. Prescribed burns for the Miami Zoo units took place in early February, 2020, and post-burn flights were flown on February 16, 2020.

All UAS flights occurred within two hours before or after civil high noon and were flown at or below 61 m (200 ft.) altitude. A flight log was completed for each flight as described in the *Methods* Section. The resulting, year-long set of monthly UAS images is one of, if not the first, UAS image catalogs of the S FL PR habitat.

Table 1. Total number of automated UAS flight surveys flown at Navy Wells from January 17, 2019 to February 22, 2020

Site Unit Name	Number of flights
2A	25
2B	15
5 - solution hole	7
5 - Everglade's bully	3
5- FL brickell-bush	1
4	7
6	2
1 (also called 2A west)	1
3 (also called 2B south)	1
Total	62

Processed UAS imagery

UAS Orthomosaic and use of the VARI for RGB data

Figure 26 provides the first post-fire, t-c orthomosaic image of the Unit 2A fire-footprint two-weeks post-fire. Figure 26 also includes the same image processed using the VARI. The orthomosaic, and VARI images of the same location flown a yr. later (February 19, 2020) are in Figure 27.

The orthomosaic image in Figure 26, shows a distinct fire-footprint of burnt-pine and open ground cover (white limestone and ash). The VARI process in the same Figure illustrates the fire-footprint. The VARI image was specifically processed with manually set index values of +0.1 to -0.1, rather than the automatically (Auto) calculated range, and a "heat" color palette to highlight the fire-footprint. The burned area, and lack of green vegetation, including in the pine canopy, is bright blue; the exposed ground cover of ash and limestone are green (seen as the white shade in the t-c orthomosaic). The red shade in

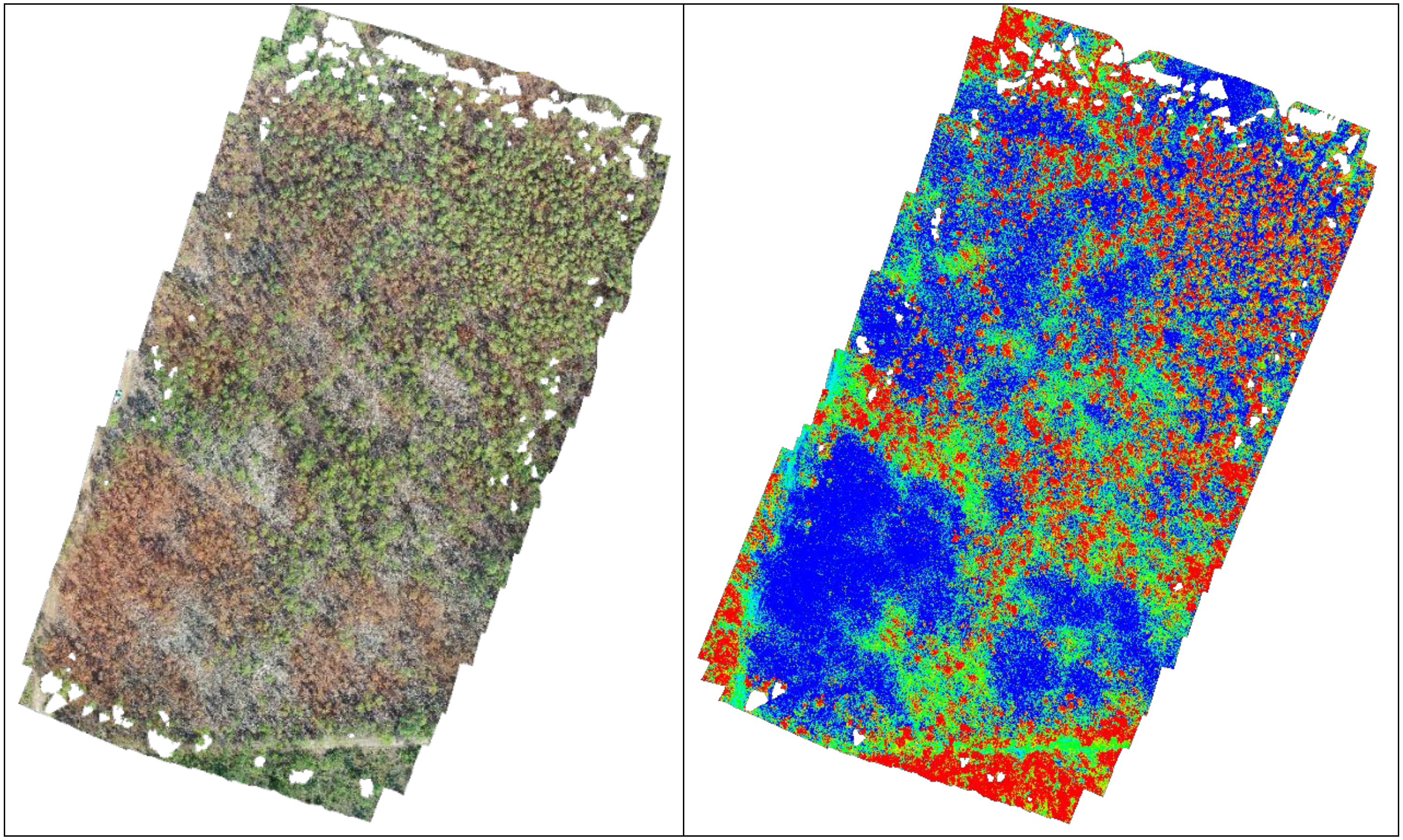


Figure 26. Navy Wells Unit 2A Orthomosaic and VARI +-0.1 heat palette. February 16, 2019; 2.1 ha (5.3 ac); 59 m (194 ft) altitude.

the VARI image is the mostly, unburned pine canopy vegetation, shown as green vegetation in the orthomosaic. An area of unburnt pine canopy is most noticeable (red) in northeast corner (top-right) of the image.

The orthomosaic (and VARI image) of the same flight survey flown February 19, 2020, one-yr. post-fire, is shown in Figure 27. The images provide a clear discrepancy between ground (blue), low and midstory vegetation (green and yellow), and the returning pine canopy (red). The vegetative recovery of the PR habitat a yr. post-fire at this site is noticeable with the comparison of the February 2019 (Figure 26), and the February 2020 (Figure 27) images. Monthly orthomosaic images of the fire footprint in Unit 2A and 2B, provided a time-series of recovery of the PR habitat. The VARI calculated images highlight burned hotspots, and changes between healthy and unhealthy vegetation in the orthomosaic.

During the course of the research, a total of 40 VARI images were processed using the UAS flight survey (RGB) orthomosaic images. At least one VARI was processed for each monthly survey (Feb. 2019 through Feb. 2020). Per the methods, the VARI raster images were produced using the automatic (Auto) index range, and two manually adjusted ranges of +-0.1, and +-0.3 were also used to further discriminate the spectral classifications within an image (Dell et al. 2019).

Eight flights over the Unit 2A fire footprint were processed using the AUTO VARI range, with the resulting ranges for six of these flights in Table 2. Two flights had

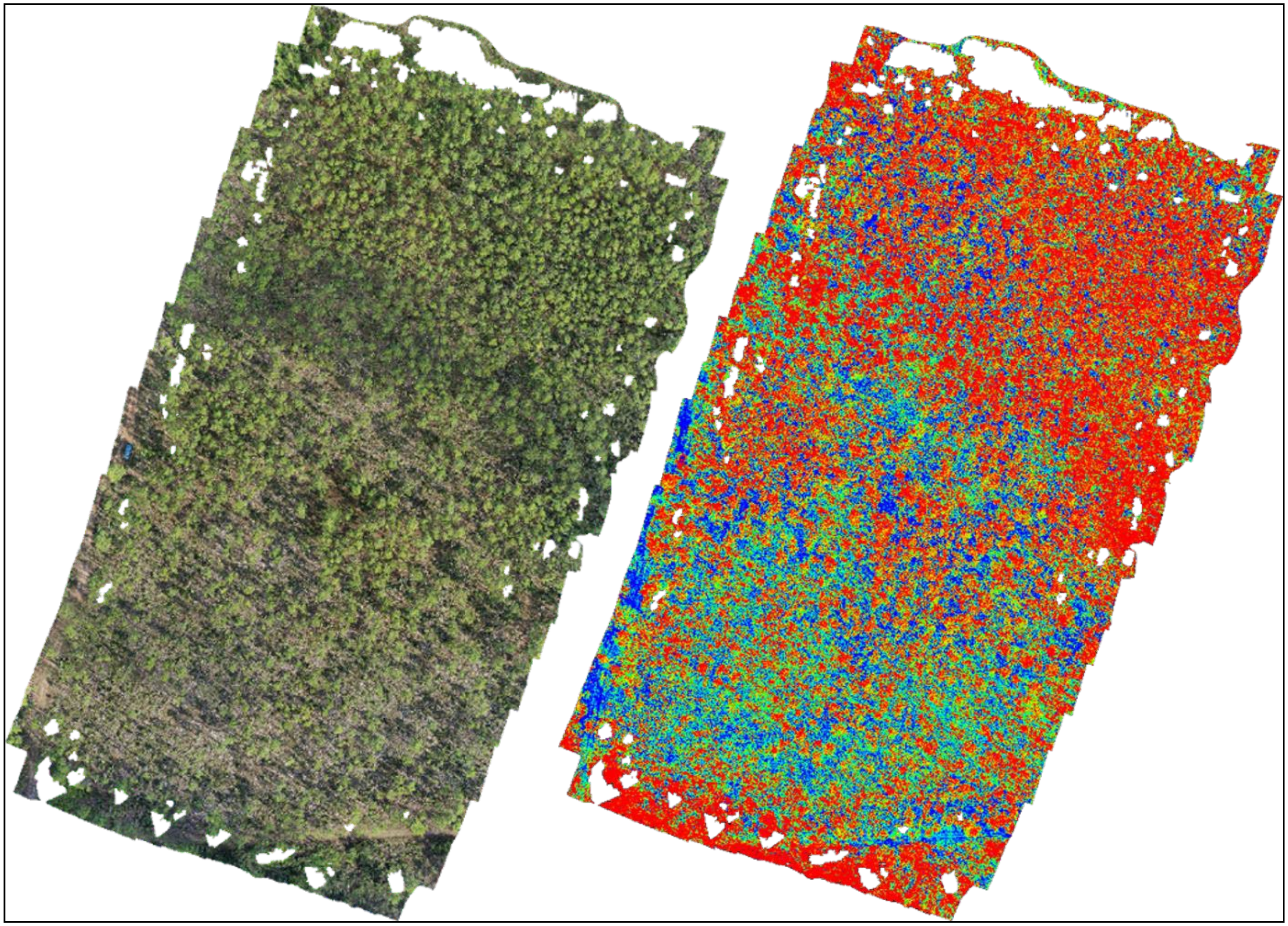


Figure 27. Navy Wells Unit 2A Orthomosaic and VARI +-0.1 heat palette. February 19, 2020; 2.1 ha (5.3 ac); 59 m (194 ft) altitude.

a “white-balance” setting error, and the resulting images were not reliable for using the index. A consistent trend in the ranges was observed over time since-fire, with ranges

Table 2. Auto VARI values for Unit 2A Navy Wells

Unit 2A Date flown*	VARI* range auto-calculated
February 16, 2019	-0.32 to +0.39
March 25, 2019	-0.27 to + 0.33
June 8, 2019	-0.20 to +0.65
August 11, 2019	-0.15 to +0.89
November 23, 2019	-0.2 to +0.72
February 19, 2020	-0.2 to +0.58

* VARIs calculated for May 2019 and January 2020 flights were not reliable due to “white balance” setting error (set “on” instead of “auto”).

exhibiting a higher positive value (representing an increase in green vegetation) from February 2019 to February 2020 images. This is expected as healthy, green vegetation returned post-fire and replaced the burnt vegetation, or exposed, “non-green” areas of limestone and burnt pine needles in the image. The VARI is a measure of the level of “greenness” in an image.

The negative values of the Auto VARI results for these six flights ranged from -0.32 to -0.15, with the positive values ranging from +0.33 to +0.89 (Table 2). The VARI ranges did not indicate wide differences over time. The average Auto VARI range of these six flights was -0.22 to +0.66. The results are representative of a small sample size of just six processed images. A larger sample size and collection period could be used to ultimately establish a standard Auto VARI range or baseline indicative of healthy PR green vegetation.

The February 2019, Unit 2A orthomosaic image (Figure 28) was processed using the Auto VARI and heat palette (Figure 23; left). The calculated Auto VARI range for this image was -0.32 to +0.41. The Auto VARI range calculated for the same flight survey, flown one-yr. post-fire (Figure 22), was +-0.20 to +0.58 (Figure 23; right). The differences in the calculated Auto VARI ranges, a shift to a reduced negative and an increase in the positive end of the range indicates the recovery trend of green vegetation over the yr. The comparison of the images (Figure 28) illustrates an increase in the "evenness" of the 2020 image and the PR vegetation at this site one-yr. post-fire (Figure 28; right).

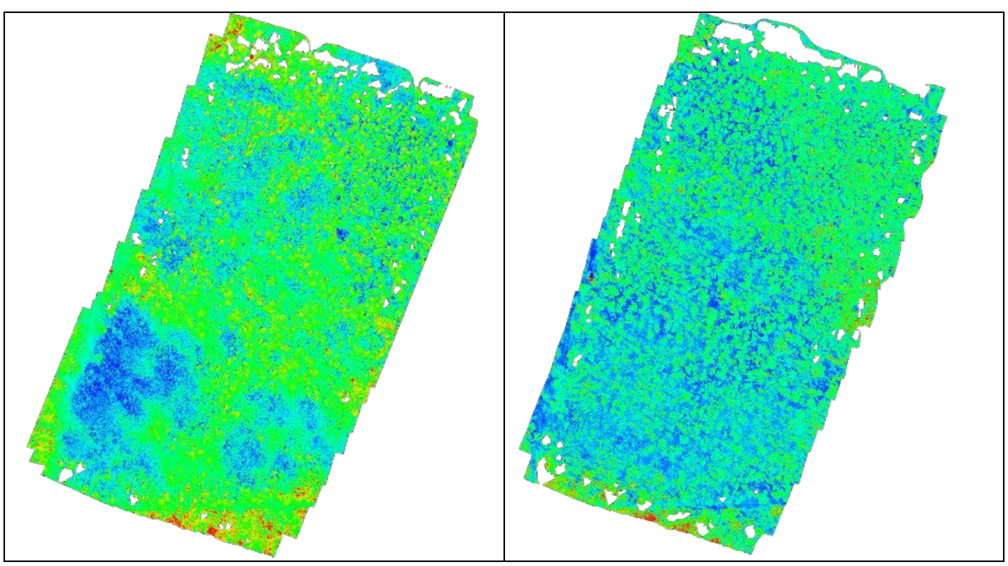


Figure 28. Unit 2A, February 16, 2019 Auto VARI -0.32 to +0.41; heat palette (left). February 19, 2020 Auto VARI -0.20 to +0.58; heat palette (right).

The spectral and textural definition of burnt, heavy shrub compared to a less-dense midstory of PR habitat was identifiable in the UAS imagery. The orthomosaic and VARI images of the fire footprint in Unit 2B (Figure 29 a and b) resulted in spectral differences between this unit's west side, that had previous hardwood thinning, compared to its east side, that did not have hardwood thinning. Unit 2B burned (that is, fire traveled through that site), however the dense (burned) shrub vegetation remained post-fire (Figure 29c). The VARI image is shown in Figure 29b. The east side of this VARI image, where the burned, dense midstory hardwood shrub-layer remains (shown in red), can be discriminated from the burned, open, ground story layer in the west side of the image (shown in blue). The cell photo in Figure 29c is a ground-level image of the burnt shrub on the east side of Unit 2B. The firebreak (shown as white trails) on this site is visible in the orthomosiac image (Figure 29a).

In Figure 30, Navy Wells Unit 3, the overgrowth of the invasive Brazilian pepper (*Schinus*), a tall and very dense shrub is evident on the east end of the orthomosaic (Figure 30a), and VARI images (Figure 30 b and c). The remaining western two-thirds of the images show some shrub overgrowth, as seen in the red spectral signature in Figure 30c, the +- 0.1 VARI, but the shrub is not as dense as the invasive Brazilian pepper. Hardwood reduction last occurred at in Unit 3 approximately eight yrs. ago however, the area of Brazilian pepper did not have thinning or hardwood removal at that time due to lack of manpower and funds. The different VARI images of this unit compare the Auto (Figure 30 b), and the +-0.1 manually set index range (Figure 30 c). The +-0.1 range

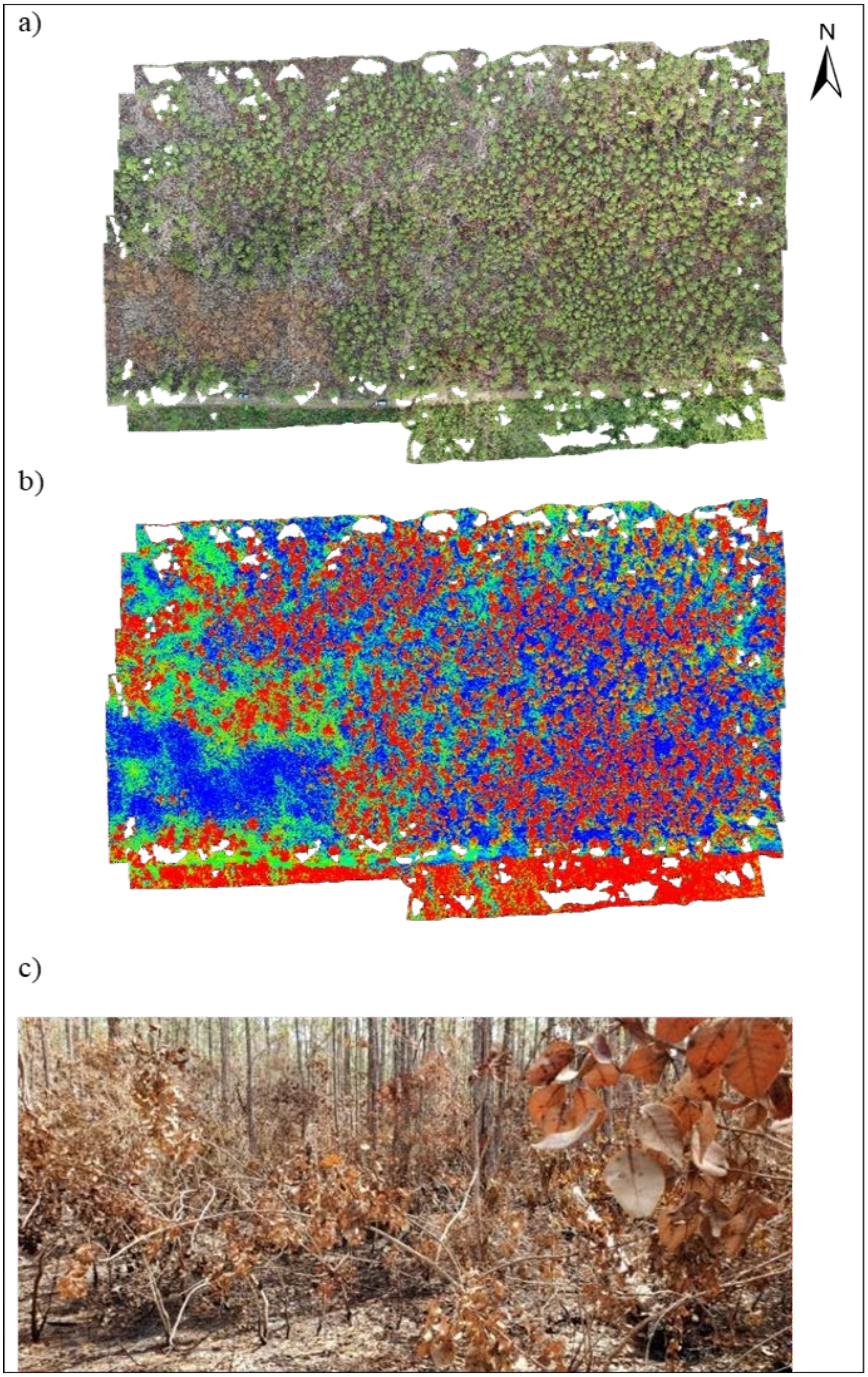


Figure 29. Unit 2B February 16, 209 post-burn orthomosaic (a) and +- 0.1 VARI (b), 60 m (197 ft) altitude, 2.1 ha (5.3 ac); c) photo image of heavy shrub remaining post-burn.

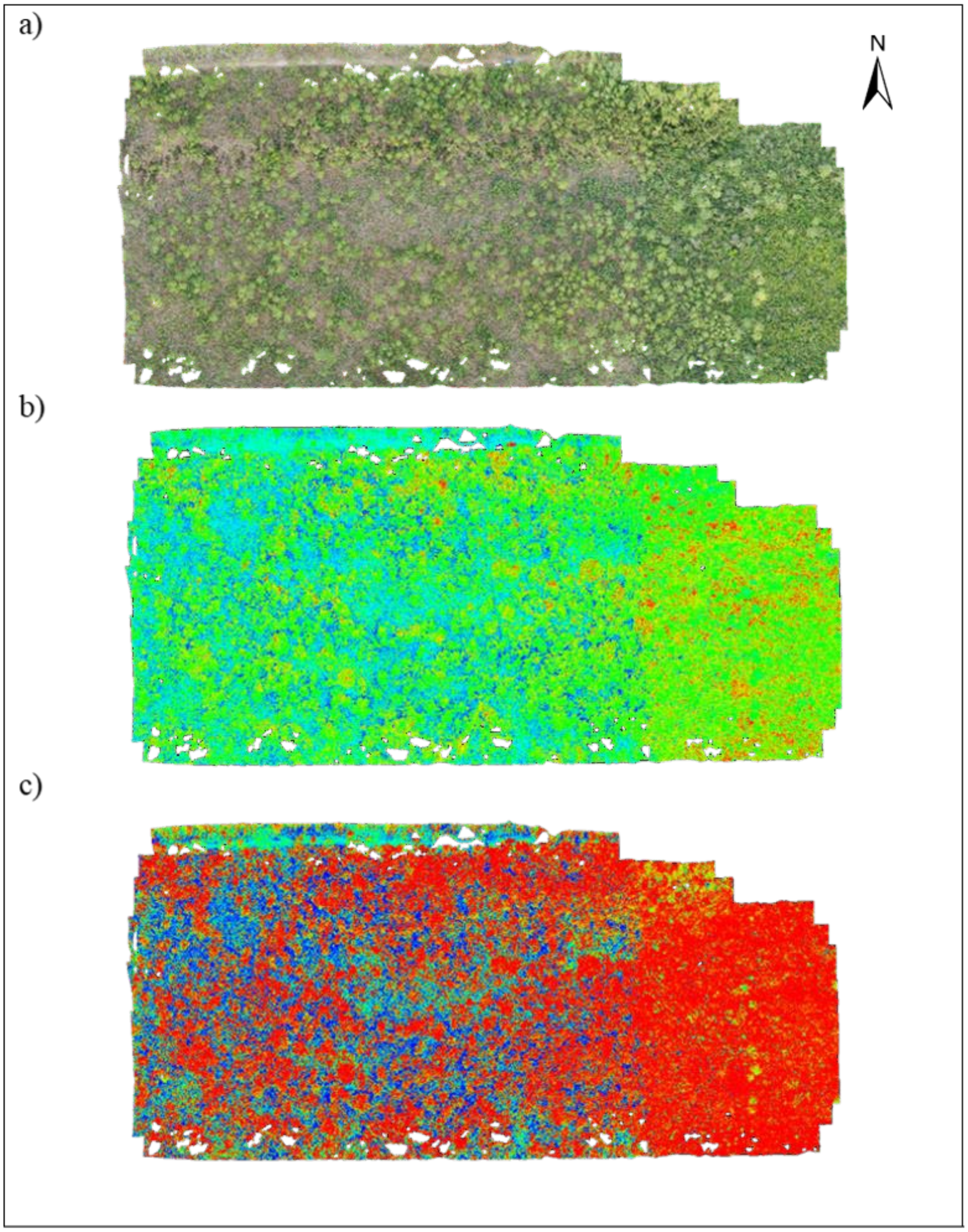


Figure 30. Unit 3 Navy Wells, January 25, 2020. (a) Orthomosaic, (b) Auto VARI, -0.28-+0.38; heat palette, (c) -0.1 to +0.1 heat palette. 51 m (167 ft) altitude.

(Figure 30 c) highlights the dense overgrowth of the Brazilian pepper shrub (red color; dense texture). Both VARIs use the heat palette.

Unsupervised and Supervised image classification

Unsupervised and supervised group classification and spectral separation of the orthomosaic images produced from UAS flight surveys were processed using ArcMap 10.8 to discriminate and visually represent the distinct spectral classifications of the PR habitat. Both the supervised and unsupervised classification methods were utilized. Classifications were also developed for single LAQI .jpg images with an emphasis for examining the diversity of the PR herbaceous ground cover. Spectral signatures for S FL PR habitat types, including for the post-fire habitat, are identified in the resulting raster image classifications.

Unsupervised Classification UAS Imagery. Unsupervised classifications of the 3-band RGB orthomosaic images were processed following ArcMap procedures presented in the *Methods* Section. In the initial raster calculation processing step, thirty spectral classes (10 times more classes to the number of bands) were selected, and the optional settings were kept at default. The resulting output raster most-often resulted in thirty different pixel classes; no image resulted in fewer than 17 classes. These classes were then manually merged, and reclassified into between five to 15 separate classes, based on similar pixel colors, field verifications, and the processor's knowledge of the PR habitat, to develop the final raster image.

Trial exercises of unsupervised group classifications, selecting for more than 30 (35-40) classes were also processed to identify as many separate pixel classifications and variation (diversity) in the image. However, this increased the processing time, and the resulting rasters still produced 30 classes or fewer. These classes were merged to result in approximately ten to 14 classes in the resulting image.

The unsupervised image classification (Figure 31) processed with the February 16, 2019 Unit 2A orthomosaic (Figure 26), resulted in the identification of 10 classes of PR habitat: three variations of burnt vegetation and burnt ground (gray); three variations of the burnt canopy (orange/red); two variations of live vegetation (green); one variation of ground cover\limestone mix (light brown); and one variation of limestone (white). A close-up section of the resulting raster is shown in Figure 32.

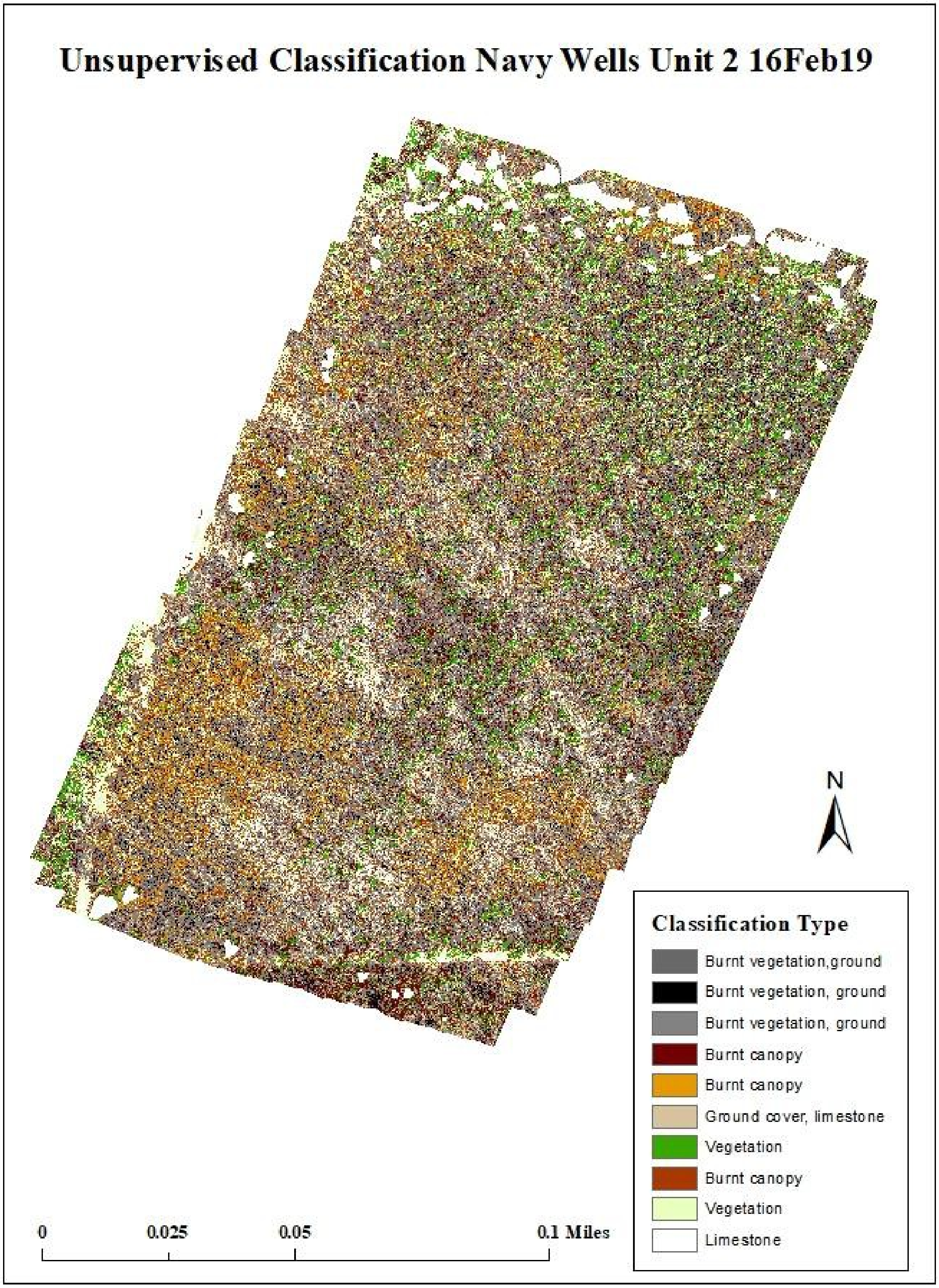


Figure 31. Unsupervised classification Unit 2A, Feb.16, 2019.

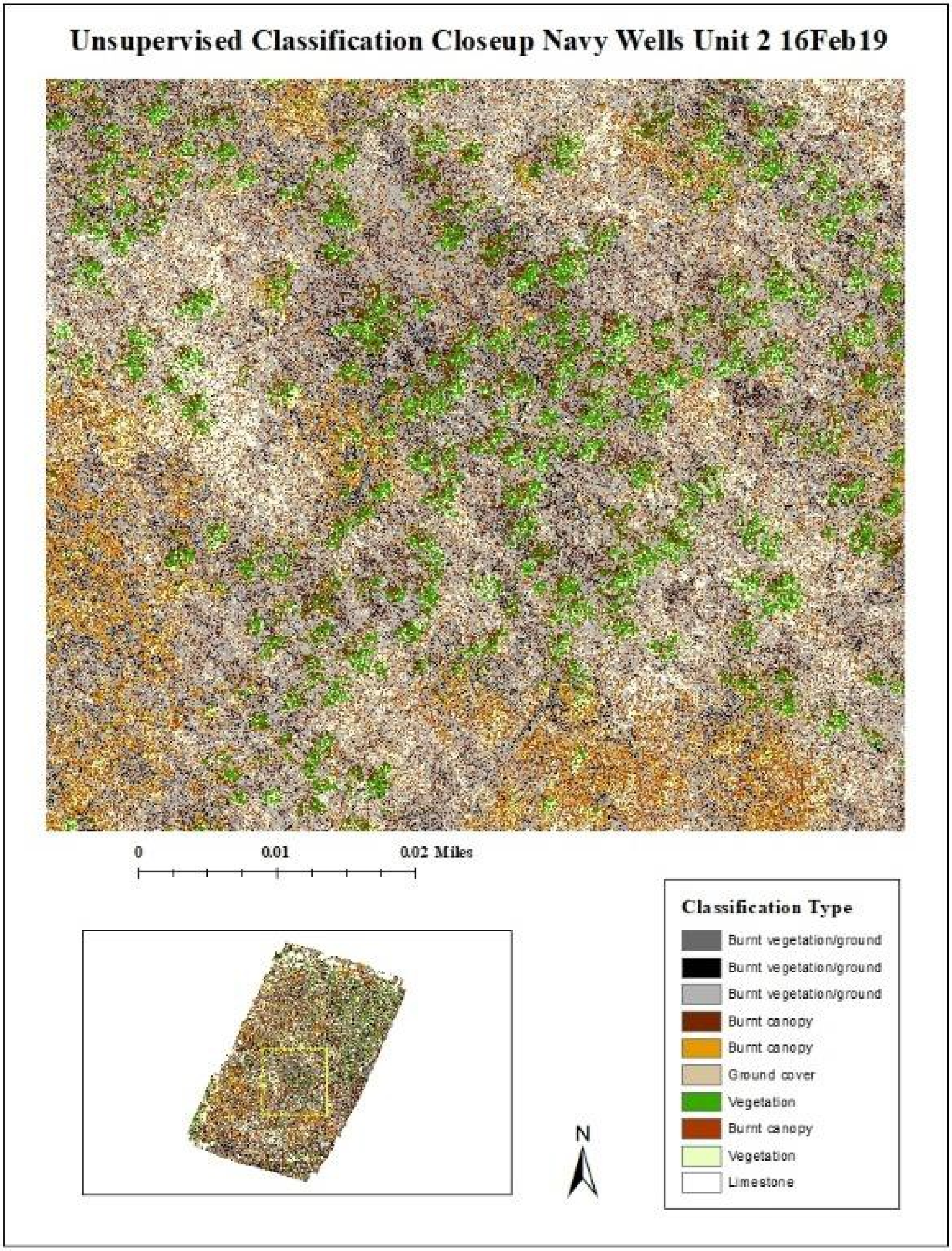


Figure 32. Close-up section of the unsupervised classification Unit 2A, Feb. 16, 2019.

The orthomosaic images of the Unit 2A fire footprint in March 25, 2019, and June 8, 2019, are shown in Figure 33, left and right, respectively, and the unsupervised images for these orthomosaics are Figure 34, left and right, respectively. The March 25, 2019 flight survey classified image (Figure 34; left) shows the reduction in "burned" group classifications since the fire. A broad extent of the exposed limestone, burnt pine needle ground cover, and burnt canopy is still evident however, signs of vegetative recovery are evident in all PR habitat layers.

The June 8, 2019 classified image (Figure 34, right) identifies grass recovery to the Redland soil area that had been bare soil (with a layer of burnt needles and organic material) immediately after the fire. The slightly depressed area at this site, with a thin layer of deposited Redland soil, and grasses, produces a unique spectral signature (mauve/light brown) compared to the green vegetative ground cover in the same image.

A close-up of the June 8, 2019, unsupervised classification (Figure 35) illustrates the level of green vegetation recovery four-months post-fire at this site. In addition to green vegetation, exposed limestone is now a major classification group in the June 8, 2019 unsupervised image (Figure 34, right, and 35). The burnt ground cover and pine needles spectral signatures identified in the February 16, 2019 (Figure 31), and March 25, 2019 (Figure 34, left) images (two-weeks and eight-weeks post-fire, respectively), are no longer identified in the June 2019 unsupervised classification (Figure 34, right, and 35), documenting the rapid shift from the burnt footprint towards recovery of the green vegetation of the PR canopy, shrub, and ground cover.

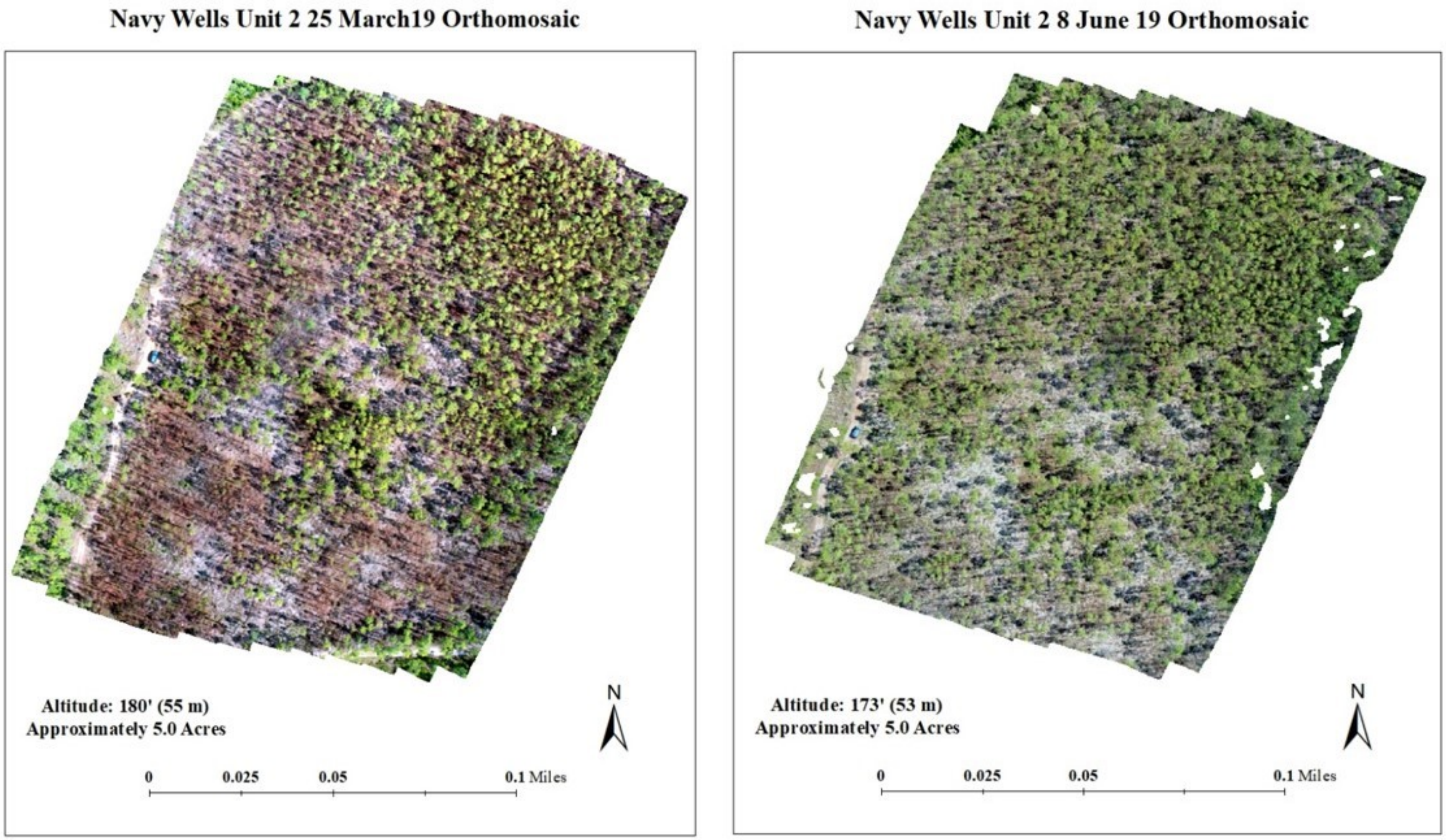


Figure 33. Orthomosaics, Unit 2A Fire footprint March 25, 2019 (left) and June 8, 2019 (right).

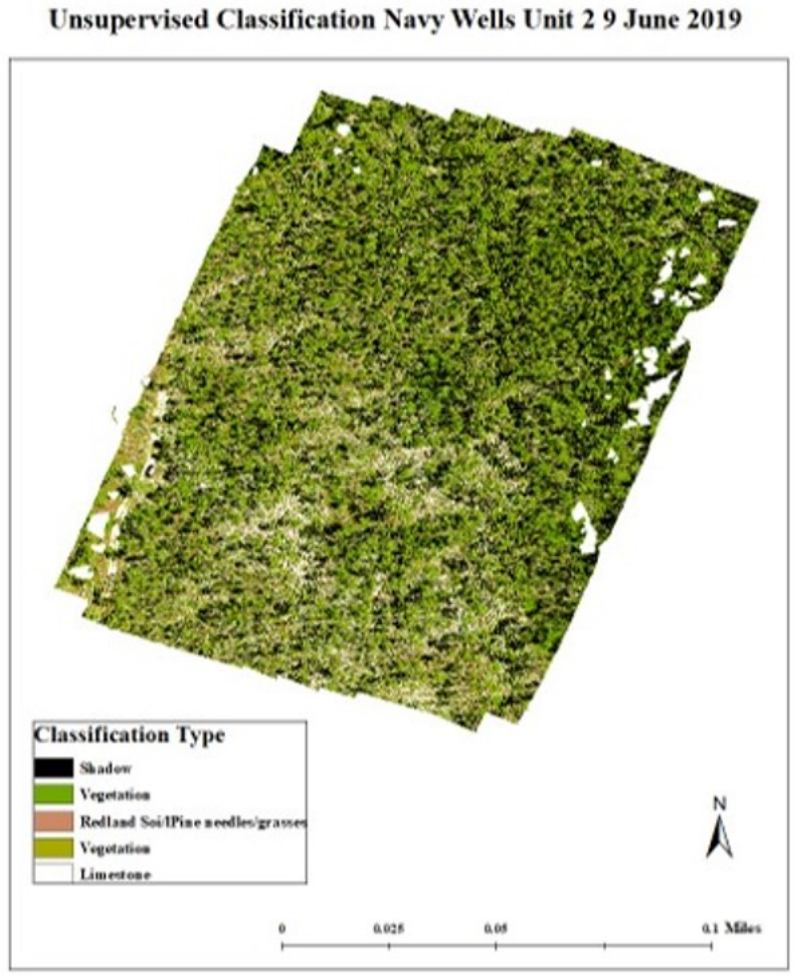


Figure 34. Unsupervised classifications, Unit 2 March 25, 2019; eight weeks post-fire (left). Unit 2A, June 8, 2019 (right).

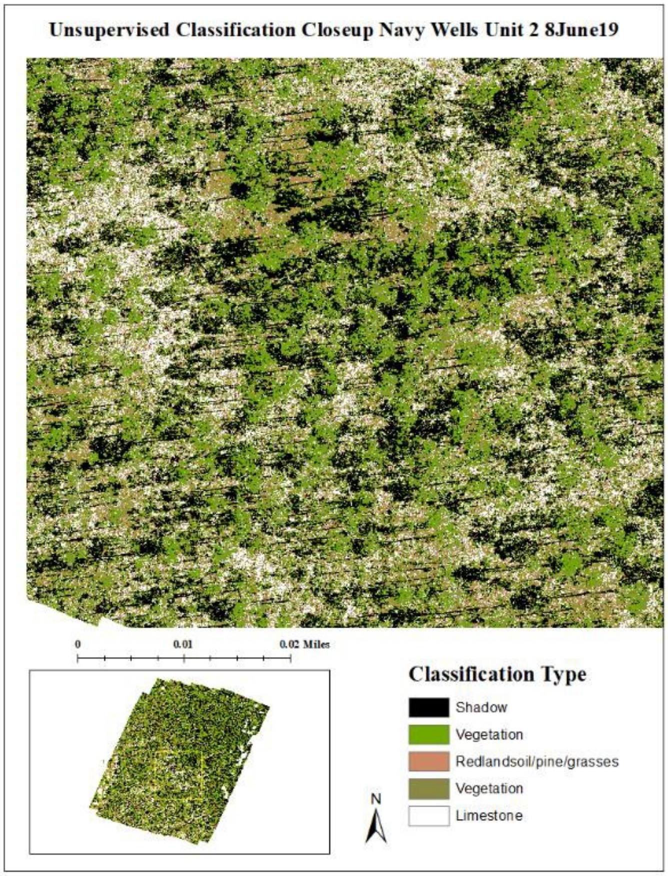


Figure 35. Closeup map of unsupervised classification Unit2A, June 8, 2019, with exposed limestone evident.

The shadow pixel group was retained in the March 25 and June 8, 2019 image classifications (Figure 34 and 35) to provide a representation and perspective on the level of open- versus shaded- ground cover; these surveys were flown at approximately 10:30 am EST, more than 2 hours before solar noon.

The resulting unique color classifications and calculated pixel count values for the Unit 2A initial, unsupervised classification of February 16, 2019, and the June 8, 2019 unsupervised image classification are provided as examples in Appendix 5.

Orthomosaic classification images of recently-burned compared to unburned, overgrown PR habitat

The June 2019 Unit 2A unsupervised image (four months post-fire) (Figure 34, right, and 35) was also compared to an unsupervised image classification processed from a January 17, 2019 UAS flight survey in Navy Wells Unit 4. Figure 36 is a close-up view of the unsupervised image. According to records, Unit 4 was last burned (prescribed burn) in 2014 and in 2007, with no records of hardwood thinning. The January 17, 2019 Unit 4 UAS survey consisted of heavy shrub overgrowth. The results of the image classifications noted a difference in the type and number of classifications (ground cover types) between Unit 4, and Unit 2, which had been recently burned and had hardwood reduction a few yrs. before the February 2019 fire. Field visits to these specific sites verified the condition of the PR habitat.

Spectral signatures for green vegetation (pine canopy, palmetto, and other shrubs) were able to be identified in the Unit 4 image classification however, the various brown spectral signatures representing dead and overgrown vegetation predominated the image (Figure 36). Palmetto shrubs consisting of old, dead or dying fronds in the Unit 4 orthomosaic image were distinguished in the image classification as “yellow” and “bright white” spectral signatures (a reflection of dead vegetation). Limestone was barely identifiable in Unit 4, except for a few areas; ground cover forbs and grasses were not spectrally identified ground cover types.

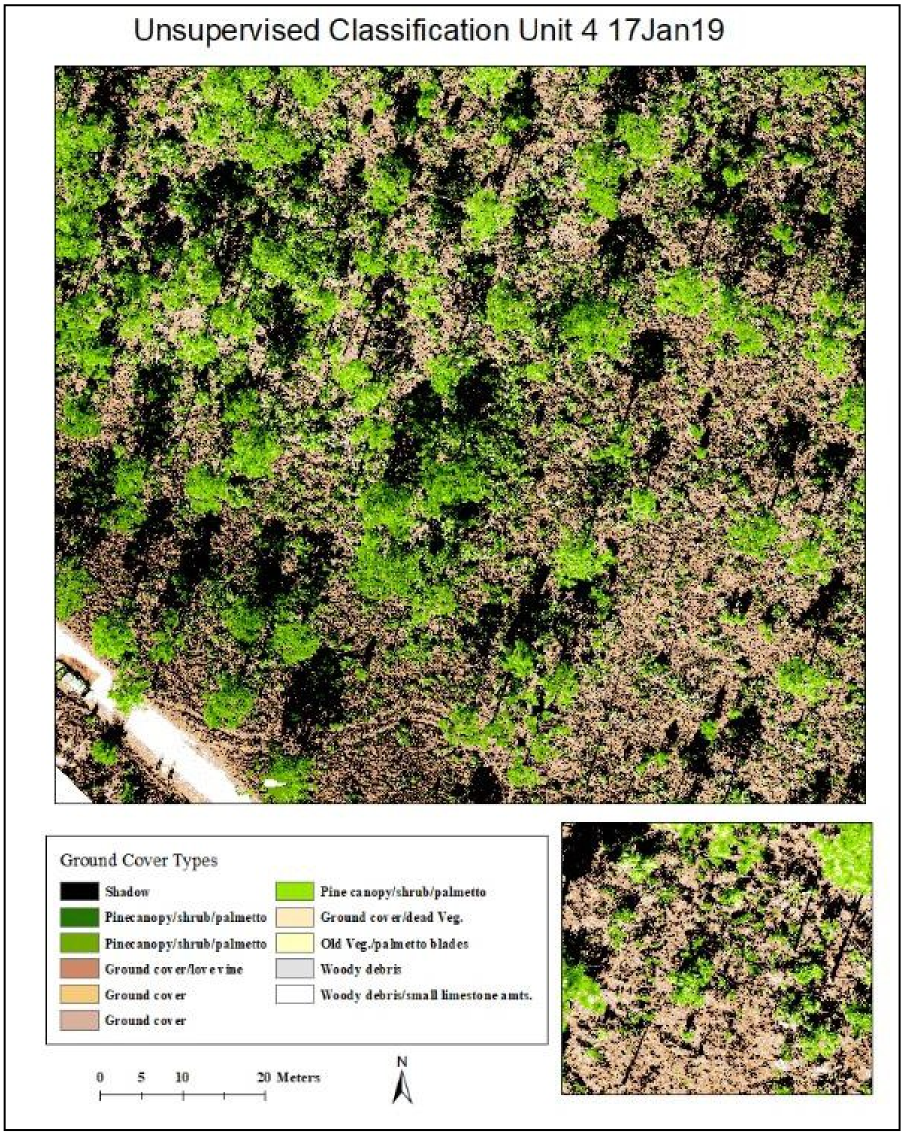


Figure 36. Map of unsupervised classification Navy Wells Unit 4, January 17, 2019.

While the Unit 4 unsupervised classification resulted in different classification types that appeared to represent system diversity, the dense shrub, woody debris, and ground cover classification types instead resulted in an overall bland spectral palette, illustrating the overgrown nature of the area compared to the Unit 2A, March and June, 2019 unsupervised images (Figure 34 and 35).

The monotypic “brown/tan” classification types in the Unit 4 (Figure 36) clearly identify different forms of overgrowth consisting of dead grasses and shrub vegetation and abundant pine needle ground coverage, dead sticks, and downed branches. The grasses and shrubs, particularly, had attached, old growth which covered the underlying herbaceous ground vegetation. These old-growth materials are built-up fuels which typically would be burned “off” with regular, low-intensity fires; giving room for healthy vegetation, like that seen in June 2019, Unit 2A (Figure 34, right).

Supervised Image Classification. As with the unsupervised processing, the resulting supervised image classifications of the orthomosaic images identified the various PR habitat classes. The supervised process was more time-intensive than the unsupervised process. However, it allowed the processor to manually select the specific habitat classes (pixel values) and gave the processor greater control in defining group types. The unsupervised image classification method was initially used in the image processing. Eventually, with the existing knowledge of the PR habitat/vegetation classifications and the direct knowledge of the habitat classes in the study site by the PI, the supervised method was adopted and used more regularly in the processing of PR habitat imagery.

Many of the PR (vegetative) group types, and spectral signatures, developed in the supervised (and unsupervised) classifications were not completely exclusive of one another (like what would be seen with two very distinct class types, such “land” and “water”; or “forest” and “impervious surface”). A careful effort was taken during the development of the training samples, to discriminate between the existing habitat classes while still retaining as much complexity and diversity (pixel values) in the resulting image as possible. The close image inspection of shapes and texture during the development of the training samples, the use of ground verification information, and a knowledge of the PR habitat types, assisted in discriminating between shades and group classes. Best efforts were made to separate individual group or class types. Additional training sample processing methods used to assist in the identification and separation of classes included: 1) creating large training areas; 2) processing in some cases being performed more than once for an image; and, 3) the separation of certain habitat group types into more than one class (such as creating an individual training area for the extreme top of the otherwise green pine canopy that shows up as "yellow" in bright sunlight).

Due to the low UAS flight altitudes, some distortion or blur in the tops of some of the taller pine trees would be present in the orthomosaic images. Any areas of distortion in the image were not used in the creation of the training sample group types.

A Histogram-Equalization (stretch renderer) was also run to improve the variation between similar classes for the February 19, 2020 supervised classification image. The "stretch" of the green band improved separation between the a) grass and limestone ground cover, and b) bright green canopy and individual shrubs. Further processing with the filtering or boundary clean tool was not performed. Although these tools can "clean up" and remove small areas within an image, it was determined that at least some of these small areas had importance to the picture of diversity and were, therefore worth retaining.

The supervised classification images of Unit 2A: a) two-weeks post-fire (February 16, 2019), and b) one-yr. post-fire (February 19, 2020), are shown in Figure 37 and 38, respectively. Both the supervised and unsupervised image classification methods were used for the February 16, 2019 t-c image for the purpose of comparing results between the two methods (Figure 31 and 37).

Figure 37. Supervised classification map of Unit2A, February 16, 2019. 59 m (194 ft); 2.1 ha (5.3 ac).

The fire footprint and the extent of the fire across both the ground cover and pine canopy, can be clearly distinguished in the resulting supervised classification raster for the February 2019 orthomosaic (Figure 37). The extent of habitat recovery is evident

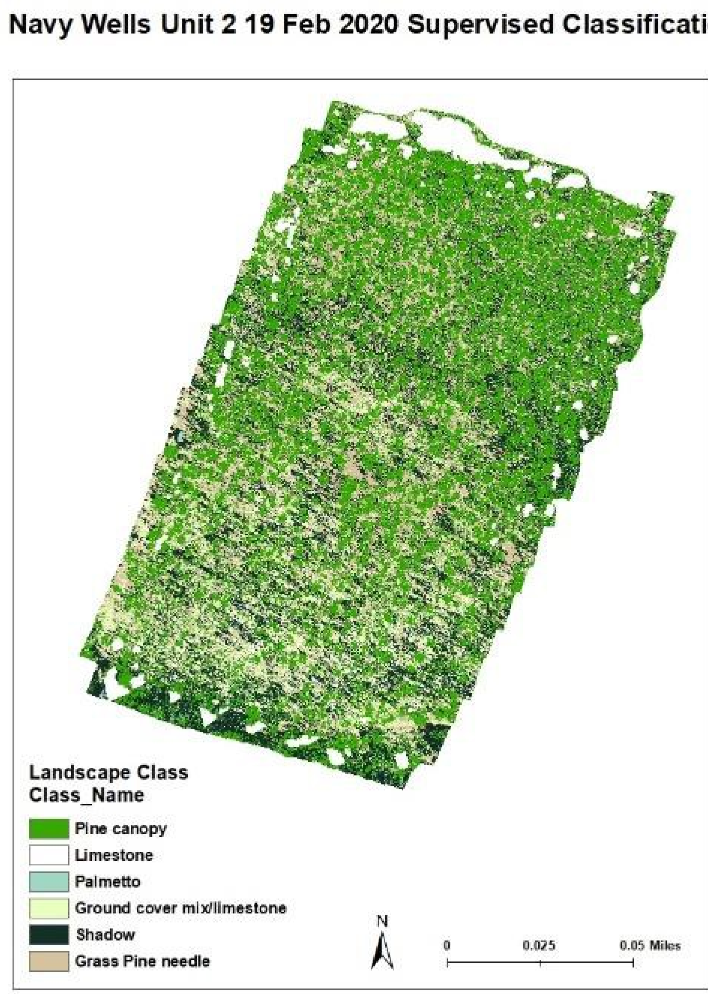


Figure 38. Supervised classification map of Unit 2A, February 19, 2020. 59 m (194 ft); 2.1 ha (5.3 ac).

with a comparison between the 2019 and 2020 supervised classification images (Figure 37 and 38). The exposed limestone was a persistent layer identified in both images, but its extent varied between the 2019 to 2020 images in relation to the amount of pine needle cover and growth of the herbaceous ground cover (return post-fire). The “palmetto” shrub group class was not identified in the February 2019 image classification, but was distinguished as separate class in the February 2020 supervised classification (Figure 38).

The discrimination and separation of habitat types in the images acquired soon after fire, such as the February 16, 2019 supervised image (Figure 37), resulted in more distinct group types than those seen one-yr. post-fire at the same site (Figure 38). As expected, the diversity of the PR habitat and its many variations in green, gray, and brown/mauve pixel values resulted in some overlaps of spectral signatures between group types. For example, “pine needle ground cover” generally appeared as a light-mauve pixel tone. Also, at times, exposed limestone under the pine canopy shade, or certain spectral shades of grass also displayed a very similar mauve tone. The PR (green) vegetation group types particularly (including the forbs, grasses, emerging shrub, pine, and palmetto), resulted in similar green shades with overlapping spectral signatures. This overlap increased as the diversity and abundance of the vegetation re-established post-fire and the resulting images became more complex. In the February 2020 supervised image (Figure 38), pixel values for shades of green of the newly emerging “shrub” class, and the “herbaceous ground cover” class were very similar and too difficult to separate into individual classes and are therefore identified in the images as a single “ground cover mix” class.

Scatterplot and histograms, all classes

Scatterplots and histograms (graphs) displaying the spectral signatures of the resulting supervised classification rasters were produced using the training sample analysis option in ArcMap. These graphs illustrated the level of separation and overlap between the spectral signatures, and allowed for further examination of the relationship between the class types within a resulting raster. The three graphs in each histogram or scatterplot are representative pixels from Bands 1, 2, and 3.

The spectral signature scatterplot and histogram for *all identified habitat classes* in the supervised classification image for the February 16, 2019 Unit 2A orthomosaic (Figure 37) are displayed on the print screen images in Figure 39 and 40, respectively. The resulting class types for the February 2019 image were: burnt canopy; burnt ground (soil with charcoal); limestone; and canopy (live green) vegetation (Figure 41). Similarly produced graphs for the February 19, 2020 supervised classification image of this site (Figure 38) are shown in Figure 42 and 43. The classes identified for the February 19, 2020 supervised image were: ground cover/limestone mix; grass/pine needles; limestone (exposed); palmetto; shrub; and canopy (live) vegetation (Figure 44). The "shadow" class type was retained in the supervised classification images when processing the 2019 and 2020 images. Since this class did not contribute to the review of the other class types, it was not selected for display, and its spectral signature does not show up in the graphs.

The February 16, 2019 histogram (Figure 39), illustrates the predominant spectral signatures of the burnt canopy (light orange) and burnt ground vegetation (dark orange) classes. The unburned pine canopy (green) and distinct "exposed limestone" layer (white) are also evident. A “ground cover vegetation” class is absent, as expected soon after fire. The “burnt ground” class includes all burnt and singed lower habitat vegetation, as well as burnt pine needles that had dropped. The other spectral signature, “charcoal soil” (gray), includes the charcoal and ash on the ground. The supervised image and graphic results also provide information about the fire’s characteristics, such as the heterogeneity

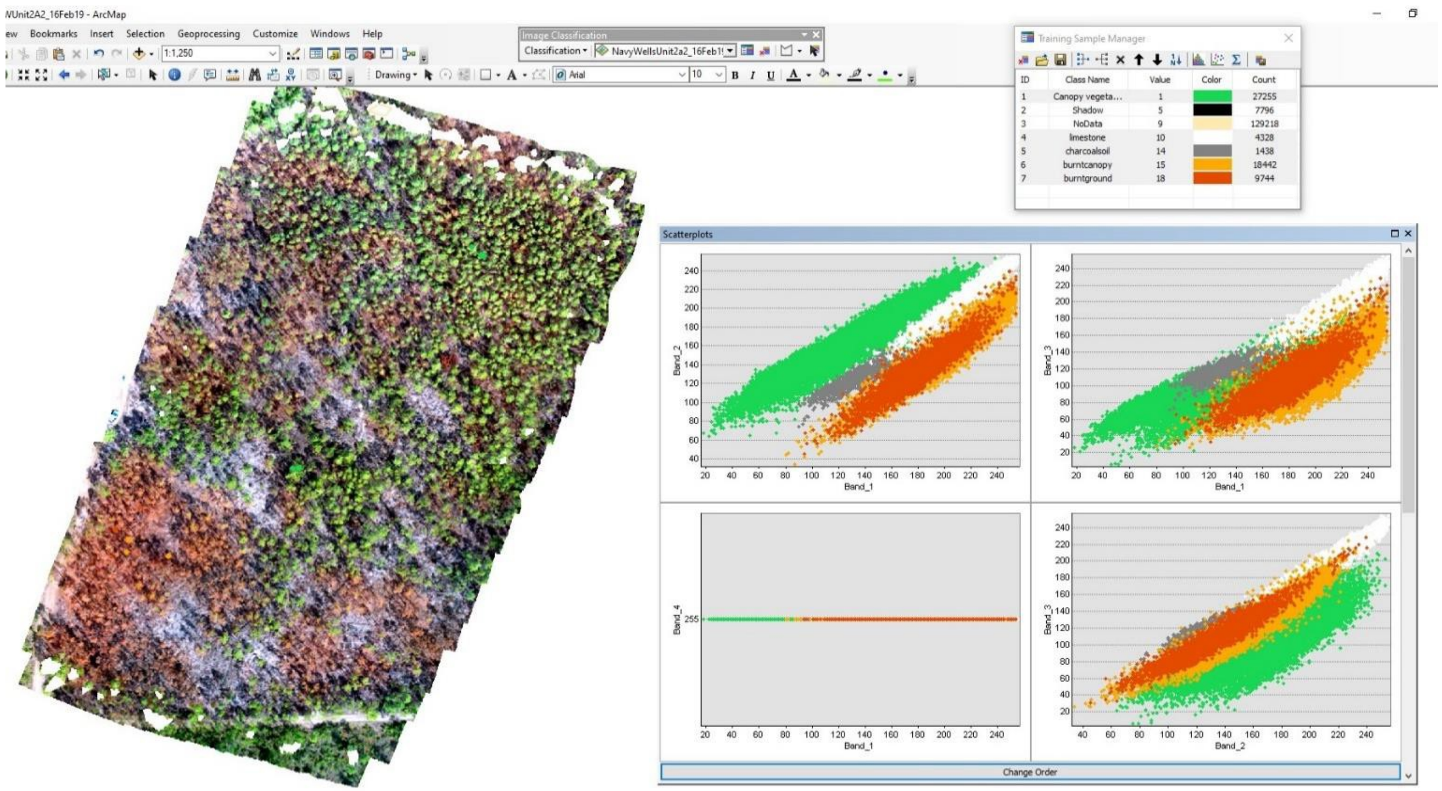


Figure 39. February 16, 2019 Unit 2A t-c orthomosaic and supervised classification scatterplot with all classes shown.

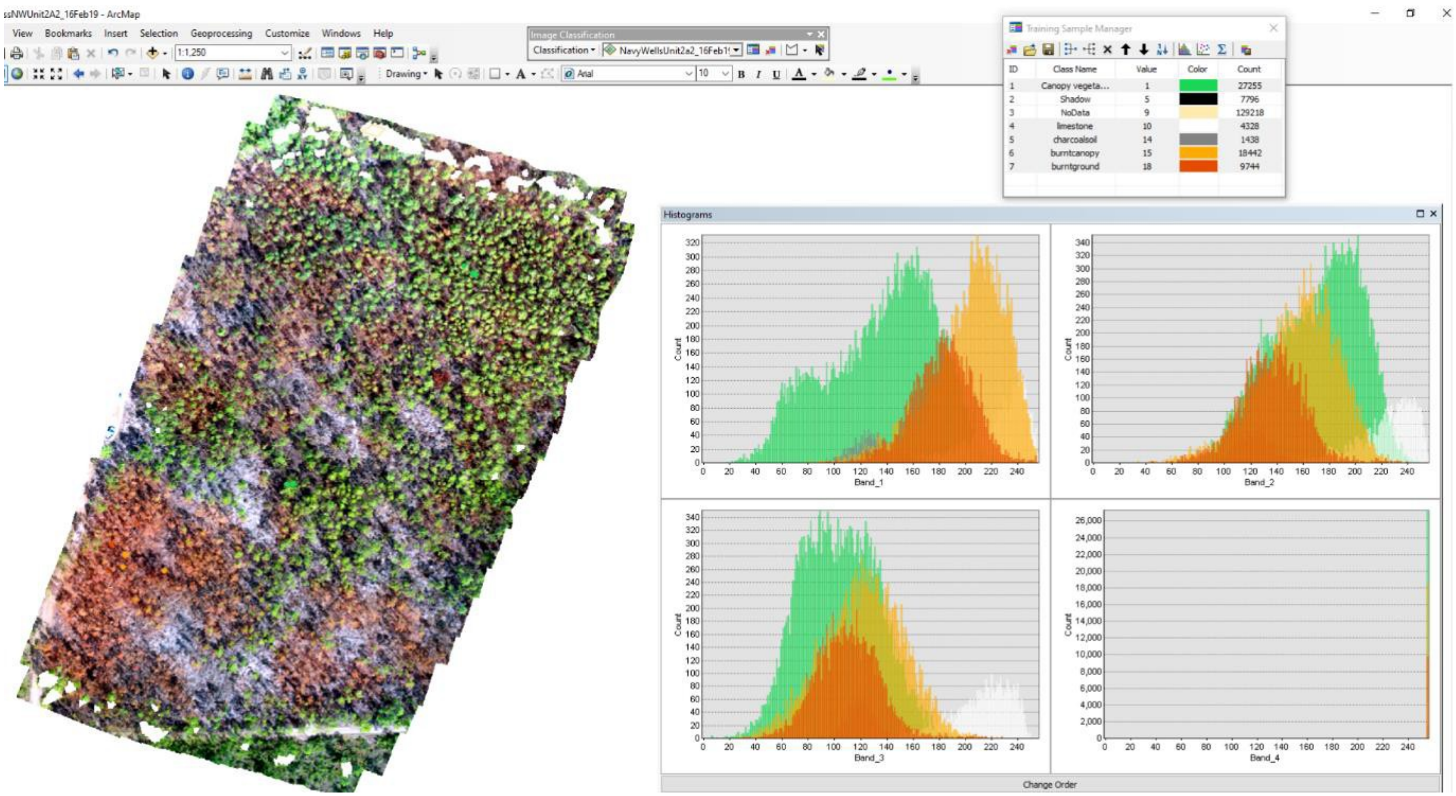
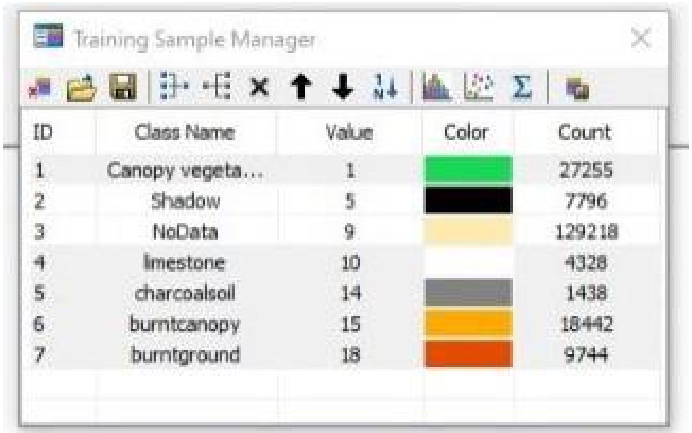


Figure 40. February 16, 2019 Unit 2A t-c orthomosaic and supervised classification histogram with all classes shown.



Training Sample Manager

ID	Class Name	Value	Color	Count
1	Canopy vegeta...	1		27255
2	Shadow	5		7796
3	NoData	9		129218
4	limestone	10		4328
5	charcoalsoil	14		1438
6	burntcanopy	15		18442
7	burntground	18		9744

Figure 41. Closeup print screen image of Training Sample for All Classes; Supervised Classification February 16, 2019.

of the burn, and the extent of impact to the pine canopy.

Noticeably different classes occur between the immediate post-fire image and the image of the same site acquired one-yr. post-fire (Figure 37 and 38). Changes and trends in the “pine canopy” and “limestone” classes are observed between the 2019 and 2020 supervised images. The return of shrubs as a habitat class is documented between the February 2019 and 2020 images. Distinct spectral signatures were identified for grassy areas, and palmetto in the February 2020 graphs (Figure 42 and 43) that are not present in the 2019 image. Figure 42 and Figure 43 show the scatterplot and histogram, respectively, for *all class types* in the February 2020 supervised classification image, identifying the variety of vegetation classes that occur at the site, compared to classes identified in the February 2019 supervised image (Figure 37). The presence of a “pine needle ground cover” class persisted throughout the yr. (identified in 2019 as part of the burned ground cover), but the spectral signature of this class shifted from the “fire-burnt, orange” shade to a more subtle “mauve/light orange” shade (fresh fallen).

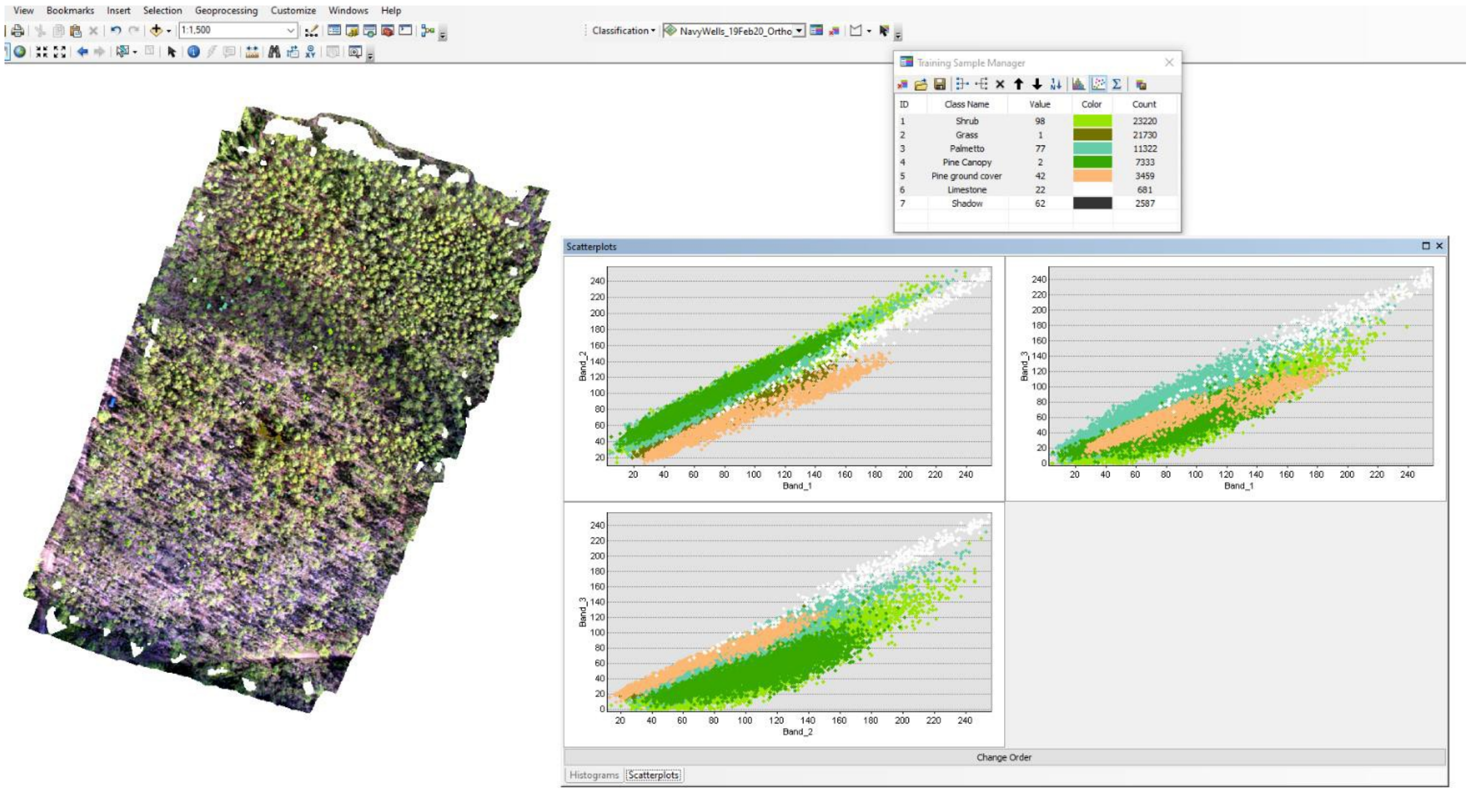


Figure 42. February 19, 2020 Unit 2A t-c orthomosaic and supervised classification scatterplot with all classes shown.

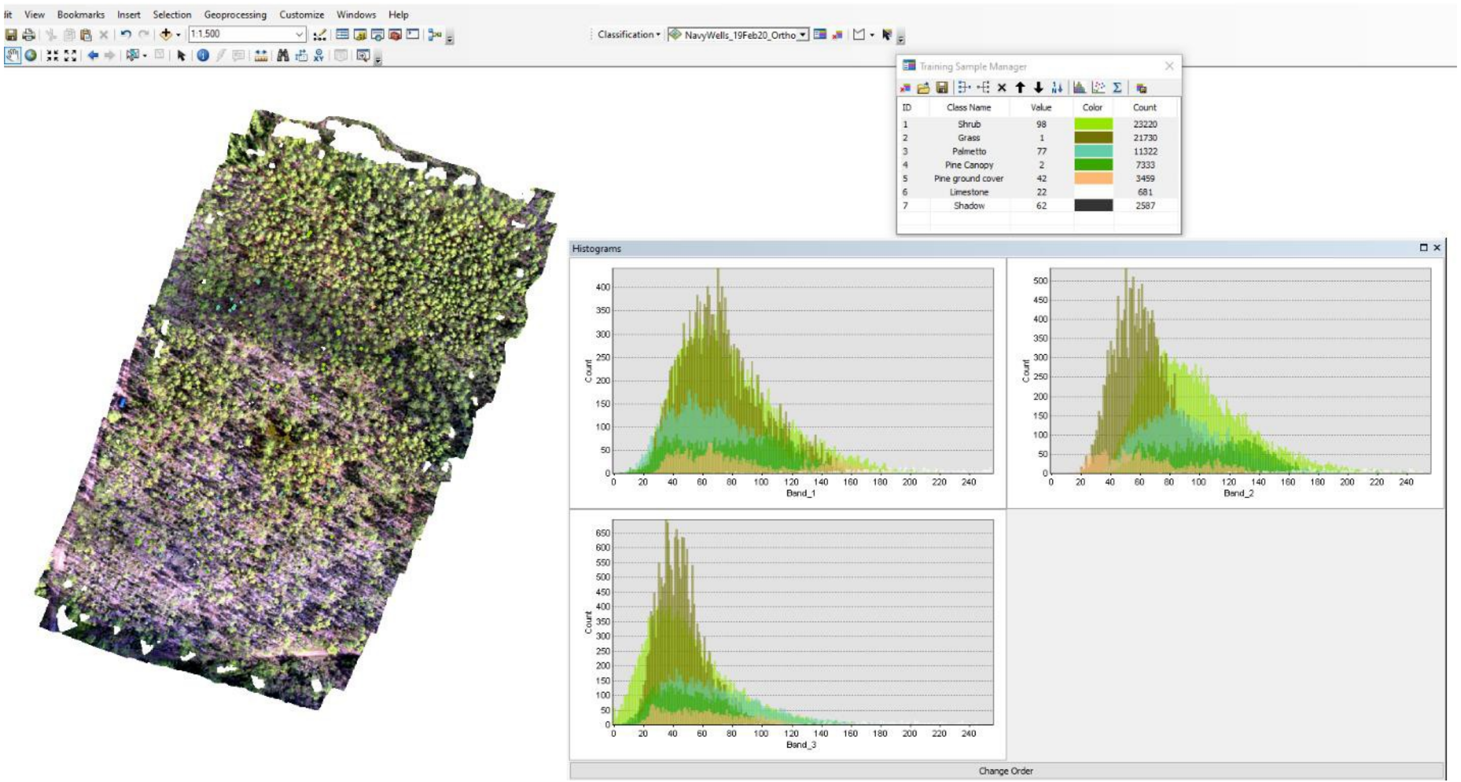
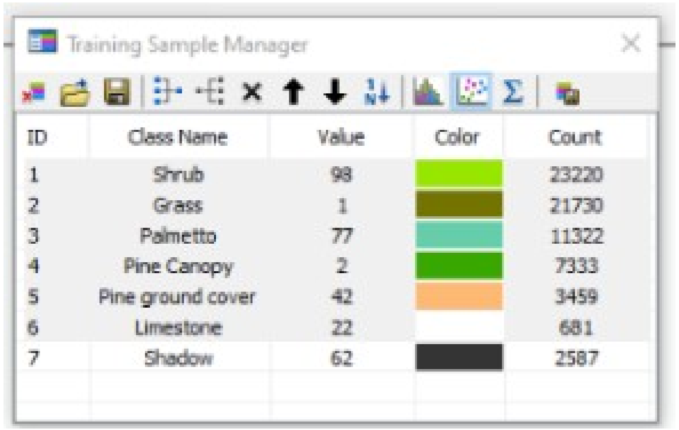


Figure 43. February 19, 2020 Unit 2A t-c orthomosaic and supervised classification histogram with all classes shown.



ID	Class Name	Value	Color	Count
1	Shrub	98		23220
2	Grass	1		21730
3	Palmetto	77		11322
4	Pine Canopy	2		7333
5	Pine ground cover	42		3459
6	Limestone	22		681
7	Shadow	62		2587

Figure 44. Closeup print screen image of Training Sample for All Classes; Supervised Classification February 19, 2020.

Only a few habitat classes are identified in the PR habitat soon after the fire, and although there is an obvious absence of mid-story and ground-cover (green) vegetation in the PR habitat in the initial 2019 post-fire supervised classification (Figure 37), site visits, and the under-the-canopy LAQI flights during this same time, documented the early emergence of individual herbaceous plants, grasses, and shrubs at the ground layer (See next *Results, LAQIs* Section).

The PR classification types identified via the supervised image classification process were not statistically separated. That is, an overlap of some pixel values existed between the different classes. The strong relationships found between pixel values (color shades) of the PR vegetative classes was expected. The overlap in the spectral signatures between classes, particularly in the February 2020 graphs (Figure 42 and 43), is attributed to overlapping similar shades of green between vegetation types (such as shrubs and flowering plants [forbs]). Different stages of growth in a species can mean that a class type, such as the “shrub”, will have a shift in shades. Emerging (young) shrubs are represented by a different spectral tone (such as light green) than older shrub vegetation (darker green leaf). Shades of similar color (pixel values) in an image classification that overlap, and the degree that they overlap, will change with time and based on the condition of the habitat when the image was acquired. Highlights and shade (from sunlight) also created similar tones between the classes, such as a "brown/mauve" tone seen in "shaded limestone", "grass", and "pine needle" ground cover, which contributed to overlap between spectral signatures. Close-up imagery and site-verifications were helpful to verify classes.

The supervised classification statistic summary tables for the February 2019 and February 2020 images (Figure 37 and 38) are provided in Appendix 6. These statistics include minimums, maximums, means, and covariance for each group type as developed in the supervised classification training samples. The resulting high covariance represents overlap of spectral signatures between the classes.

Supervised classification 2020 graphs, pine canopy class removed

Using the same February 2020 supervised classification image (Figure 38), the "pine canopy" class was removed from (not selected for) the training sample scatterplot and histogram to more clearly display and focus on the separate spectral signatures of the understory vegetation classes. Removing the "pine canopy" class in the graph eliminated the overlap of its spectral signature with the other green vegetation. Figures 45 and 46 are the scatterplot and histogram, respectively, showing the "under the canopy" layers in the February 2020 supervised image: shrubs, palmetto, grasses, pine needle ground cover, and exposed limestone. These are the same supervised training samples as seen in Figures

42 and 43 (all classes; Figure 44) but the “pine canopy” class removed. Band 2 in each graph, shows the best separation of the classes.

The “grasses”, “shrubs”, and “palmettos” were the prominent spectral group types in February 2020 image (acquired one-yr. post-fire) (Figure 38). The “pine needle ground cover” remains as a group type (seen as orange shade in the histogram and scatter plot) in Figures 45 and 46 but consists of recently dropped needles rather than the noticeably-burnt pine needle layer (burnt orange) of the 2019 image (Figure 37). The exposed limestone class (white) is barely visible along the right tail of the histogram in Figure 46, but can be observed in the scatter plot (Figure 45).

In the resulting 2020 supervised classification raster image, the class name, “shrub”, includes the shrub and ground cover green vegetation due to the difficulty separating these two groups with such similar green shades, and the abundance of vegetation and the mix and complexity with these two habitat groups. As the shrubs mature, the heavier, individual shrubs could, in some instances, be separated from the smaller plants. Palmetto was very distinct in in the images, both in its teal/turquoise shade and unique frond pattern. Grasses, such as the Redland soil/grass area, tended to have a mauve/green shade and a smooth texture (except for individual grass tufts like that seen for gamma grass), compared to the more vivid green and rougher, irregular texture of the shrub and plants. The information on the spectral signatures and the pattern and design of specific species groups were used together for distinguishing between the different habitat types.

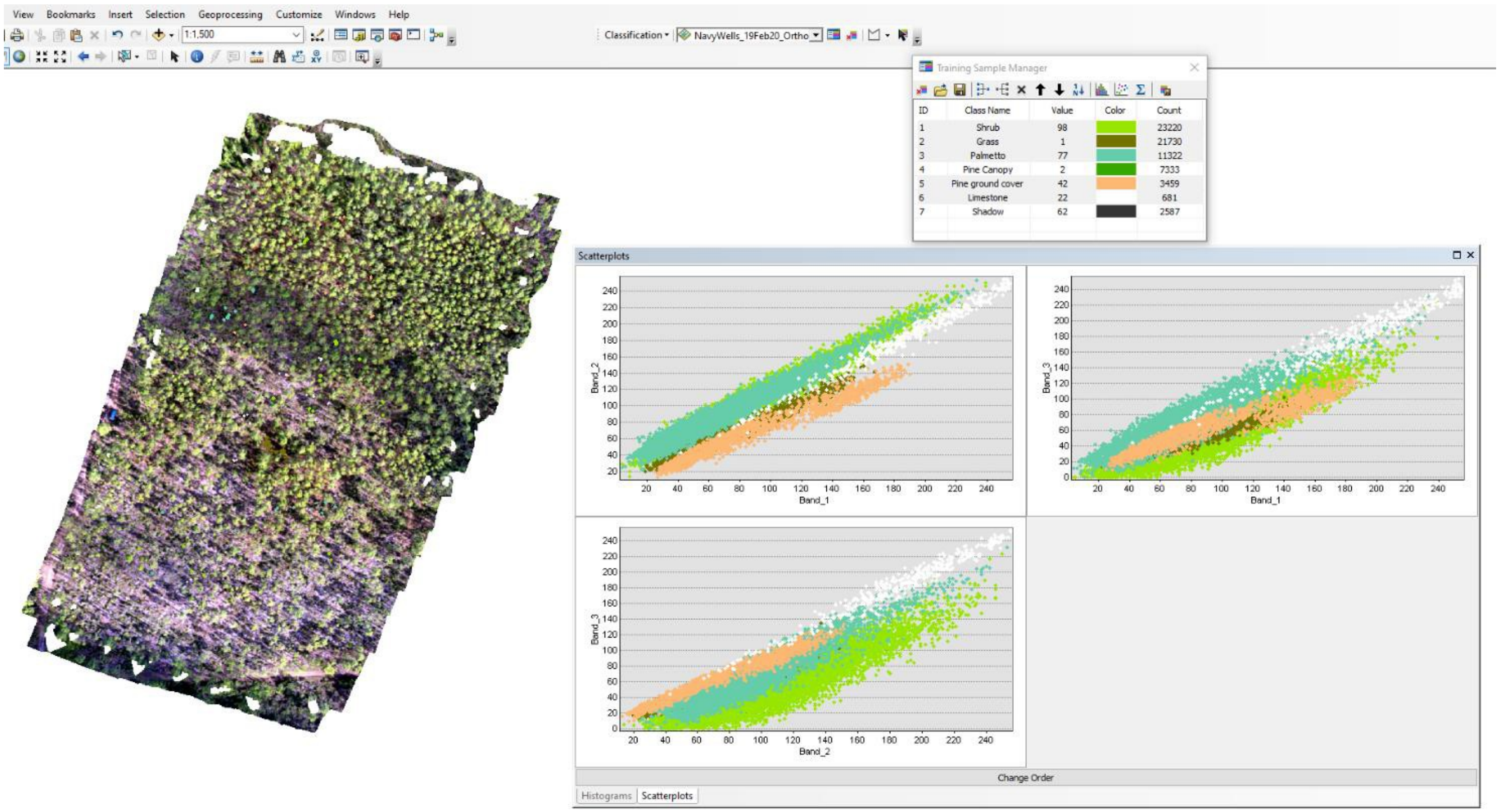


Figure 45. February 19, 2020, Unit 2A t-c orthomosaic and scatterplot of ground cover classes, with pine canopy removed.

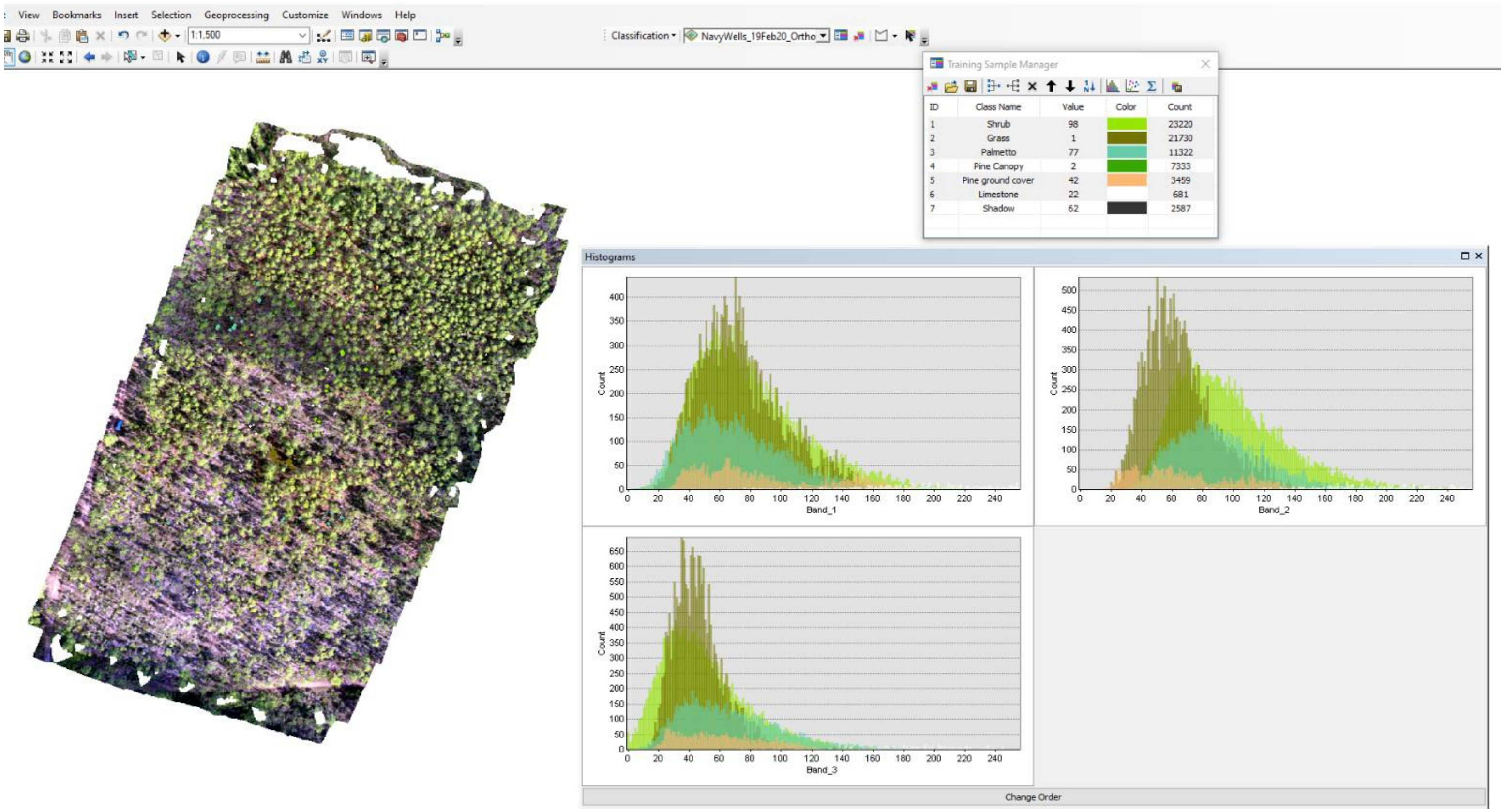


Figure 46. February 19, 2020 Unit 2A, t-c orthomosaic and histogram of ground cover classes, with pine canopy removed.

Limitations

During the development of training samples, care was taken to create the training sample to visually discriminate between group types, particularly group types that appeared similar in the t-c orthomosaic image used to build the training sample. For example, grass tufts "from above," in an aerial image, can look very similar to emerging, young pine trees in their "grass" stage (sometimes called "candlestick" stage). For this reason, it is expected that the "grass" group type is possibly underestimated.

Emerging shrubs post-fire (with first growth coming from the base of the shrub) and individual herbaceous plants can be challenging to discriminate since they have similar form and color. Limits to the resolution of the individual ground cover plants in the orthomosaic hindered perfect discrimination and separation between those plants and the young, green shrub. Direct knowledge of the site, and careful inspection of the image during the classification process contributed to the ability to discriminate between these groups. When the separation of the green ground cover vegetation types was not possible in the processing, the class type was labeled as "vegetation" or "shrub/ground cover" vegetation. The LAQI and ad hoc imagery also assisted in the verification and classification of these groups.

Low Altitude Quadrat Imagery (LAQI)

UAS flights were flown under the pine canopy to capture more detailed imagery (LAQIs and ad hocs) of the lower habitat without viewing through or removing the "canopy" class in processing. The typical above-canopy aerial flight surveys and image-classifications present a classic canopy view of the PR habitat. These above-canopy flight images are limited in their ability to discriminate the components and condition of the midstory and ground cover layer. Slocum et al. (2003) identified three main classes in the ENP PR ground cover and midstory: herbaceous grasses and forbs; shrub and palms; and fine fuel litter. The under-the-canopy UAS imagery captured unimpeded, high-definition imagery for examining the diversity of the PR understory.

The LAQI t-c (.jpg) images were used in the a) photo-interpretation of the LAQI quadrats and individual PR species indicators (WPT); b) processing of supervised and unsupervised image classifications; c) time-series examination of the monthly LAQIs; and; d) comparison with the field-verified quadrat ground cover-abundance estimates. All LAQI quadrats were created in Unit 2A within the fire footprint (except for two LAQI quadrats in 2Awest [also called Unit1]).

The center-WPT indicators (LAQI WPT) used in the LAQI flights (and field assessments) are listed in in Table 3. The detailed GPS coordinates and the date each LAQI WPT was initially created (flagged and coordinates collected) are provided in Appendix 3. Per the earlier described PI/PIC-developed methodology, LAQI images were collected each time flown from 4.6, 4.0, 3.4, and 3.0 m (15, 13, 11, and 10 ft) altitudes over each WPT indicator. Two images were taken at 3.4 m (11 ft). The "standardized LAQIs" (those UAS images acquired over the quadrat's center WPT at 3.4 m (11 ft) altitude, nadir camera) were used in the image processing and presented in these results. A small orange flag marked the center WPT indicator in each LAQI quadrat (LAQI). An example of the first and last LAQI images, and cell photos of LAQI WPT 14 (Gamma grass indicator) is in Figure 47.

Table 3. List of WPT Indicators

WPT number WPT numbers are not consecutive	**LAQI WPT Indicator name or descriptor**
011 (referred to as 2QA)	Sabal palm; *Sabal palm*
012 (referred to as 2QB)	Diverse area with exposed limestone
2QB/Deltoid	Pineland deltoid; *C. deltoidea* ssp. *pinetorum*
014	*Gamma* grass; *Tripsacum floridanum*
016	*Ipomea tenuissima;* Rockland morning glory (in limestone formation)
018	Purple thistle; *Cirsium horrigulum*
020	Locustberry; *Brysonima lucida*
021	*Tetrazygia bicolor*; West Indian Lilac
028	*Croton* linearis; Pineland croton
029	Dollarweed; *Rhynchosia reniformis*
030	Rockland twinflower; *Dyschoriste angusta*
031	*Galactia pinetorum*; Small's milkpea.
032	Lantana blooming; *Lantana depressa*
033	Bahama sachsia; *Sachsia polycephala,* and narrowleaf silkgrass; *Pityopsis graminifolia*
034	*Passiflora suberosa*; corky-stemmed passion-flower
035	Wildland petunia; *Ruellia succulenta*
041	Spurred butterfly pea blooming; *Centrosema virginianum*
042	biodiverse limestone area near 2QB
043	*Melanthera parvifolia* near 2QA
044	Purple thistle; *Cirsium horrigulum*
047	Chapman's rhododendron; *Solidago odora chapmanii*
048	Walter's ground cherry, furthest north LAQI; *Physalis walteri*
049	Devil's potato near 18; *Echites umbellatus*
055	Limestone bowl
056	*Agalinis fasciculata* blooming; Beach false foxglove
063	Clasping aster; *Symphyotrichum adnatum*

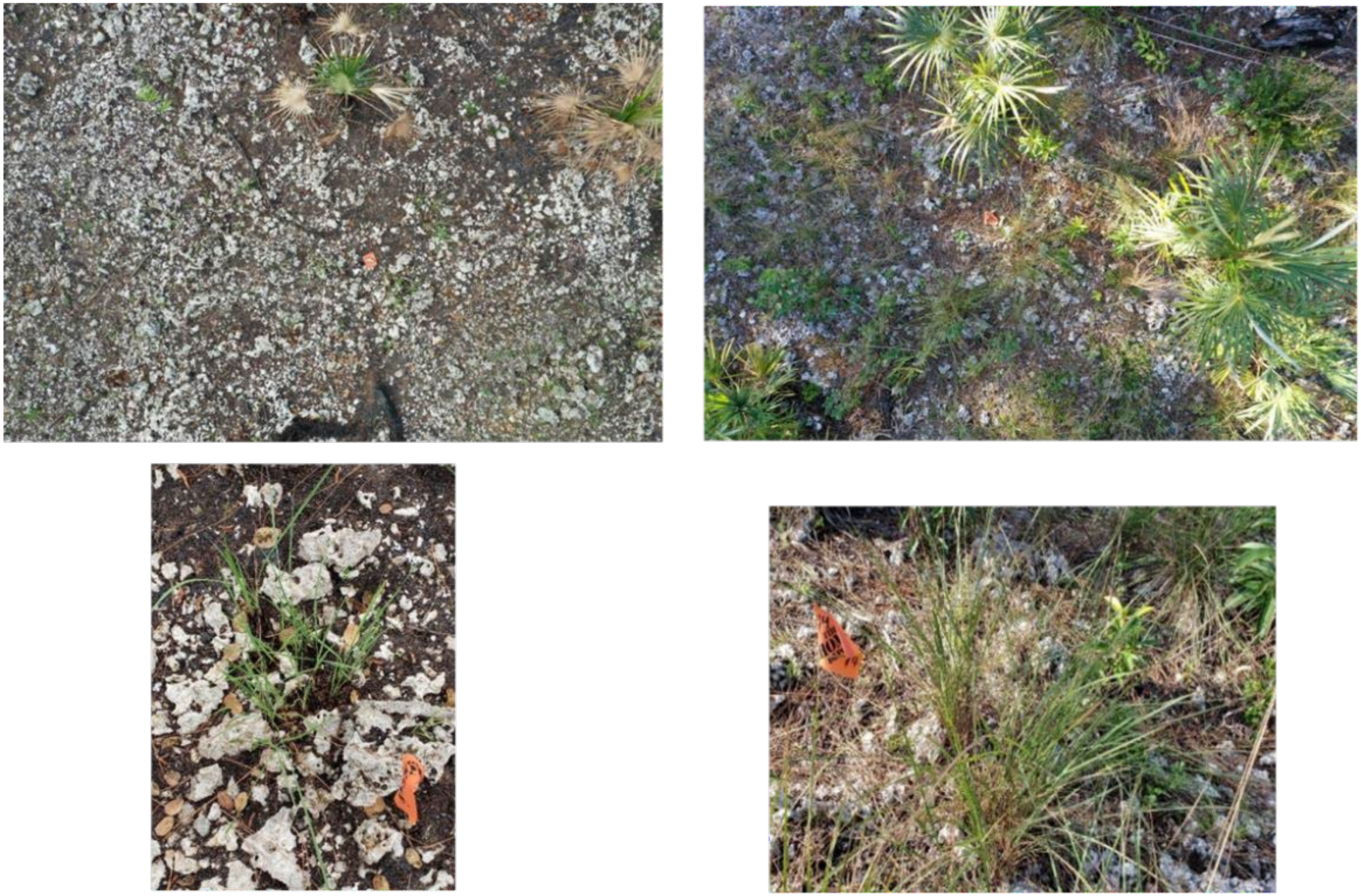


Figure 47. First (March 8, 2019) and Last (February 22, 2020) LAQI images WPT 14, Gamma grass (upper); Respective cell photos of the Gamma grass indicator (lower) marked with orange flag.

Flight log summary

Twenty-six (26) LAQI flight sessions were flown between February 24, 2019 and February 22, 2020, on either an every-other-month or monthly period. A summary of the specific LAQIs flown on each date is provided in Table 4. As the pilot's skill and efficiency in flying the standardized flight methods improved, more LAQIs were able to be flown during a single research period. Eventually, all twenty-six (26) LAQIs were flown by the pilot in a single field visit.

Table 4. LAQI flight dates

Low Altitude Quadrat Images (LAQIs)	**WPTs surveyed**
February 24, 2019	2QA, 2QB
March 8, 2019	2QA. 2QB, 2QB Deltoid
March 16, 2019	2QA. 2QB, 2QB Deltoid, 14,16, 18, 20,22, 28, 29, 30 (was22), 31, 32 (was 25), 33, [first flagged 21,34, 35- No LAQI]
March 25, 2019	34, 41
April 13, 2019	2QA, 2QB, 2QBdeltiod, 14, 16, 24, 28, 29, 32, 33, 35, 41, 42, 43 44
May 4, 2019	2QA, 2QB,2QBdeltoid, 14, 16, 21, 28, 29, 30, 31,32, 33, 34, 35, 41, 42, 43, 44
May 25, 2019	2QA, 28, 2QB, 2QBdeltiod, 14, 16, 20, 30, 32, 34, 41, 42, 43, 44
June 21, 2019	18, 20, 21, 29, 30, 31, 33, 35, 47, 48, 49
July 6, 2019	2QA, 28, 2QB, 2QBdeltiod, 14, 16, 29, 32, 34, 35, 41, 42, 43, 44
July 27, 2019	2QA, 2QB and 2QB deltoid, 18, 20, 21, 28, 30, 31, 33, 34, 35, 43, 44, 47, 48, 49, 56
August 25, 2019	2QA, 2QB, and deltoid, 14, 16, 28, 29, 32, 34, 35, 41, 42, 43
September 7, 2019	18, 20, 21, 30, 31, 32, 33, 35, 41, 44, 47, 48, 49, 56
October 5, 2019	2QA, 2QB, and deltoid, 14, 16, 18, 20, 21, 28, 29, 30, 31, 32, 33, 34, 35, 41, 42, 43, 44, 47, 48, 49, 56
November 2, 2019	2QA, 2QB, and deltoid, 14, 16, 18, 20, 21, 28, 29, 30, 31, 32, 33, 34, 35, 41, 42, 43, 44, 47, 48, 49, 56, First WPT 63

November 30, 2019	All WPTS - 2QA, 2QB, and deltoid, 14, 16, 18, 20, 21, 28, 29, 30, 31, 32, 33, 34, 35, 41, 42, 43, 44, 47, 48, 49, 56, First WPT 63
December 28, 2019	All WTPS - 2QA, 2QB, and deltoid, 14, 16, 18, 20, 21, 28, 29, 30, 31, 32, 33, 34, 35, 41, 42, 43, 44, 47, 48, 49, 56, 63
February 9, 2020	All WPTS - 2QA, 2QB, and deltoid, 14, 16, 18, 20, 21, 28, 29, 30, 31, 32, 33, 34, 35, 41, 42, 43, 44, 47, 48, 49, 56, 63, New WPT 73 (blooming thistle); white balance off.
February 22, 2020	All WPTs -2QA, 2QB, and deltoid, 14, 16, 18, 20, 21, 28, 29, 30, 31, 32, 33, 34, 35, 41, 42, 43, 44, 47, 48, 49, 56, 63, New WPT 73

Photo interpretation of t-c LAQIs and Individual Indicators. Examples of resulting individual, t-c LAQI images follow:

A. LAQI WPT 2QB/deltoid with an insert close-up image of the newly emerging pineland deltoid spurge (*C. deltoidea* ssp. *pinetorum*), March 8, 2019 (one-month post-fire): an intensely burned area. The deltoid spurge, is an ESA-listed PR endemic, and one of the first ground cover plants to return post-fire (Figure 48).

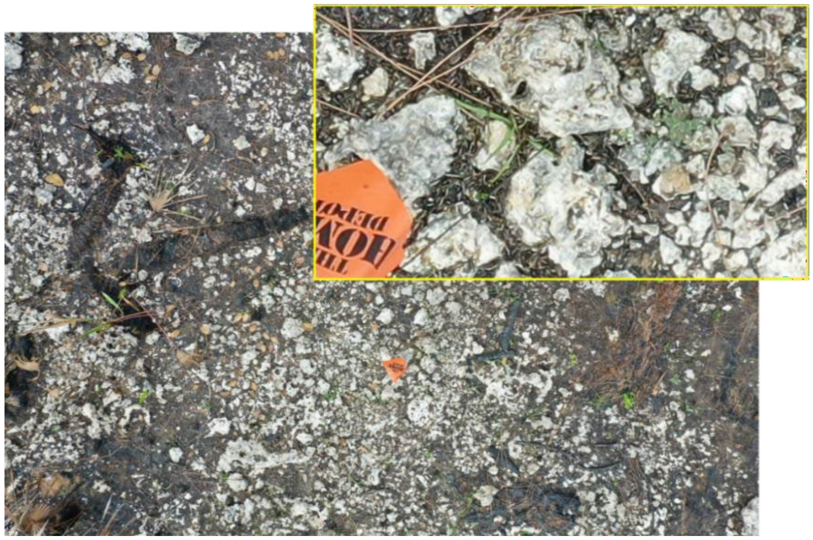


Figure 48. LAQI WPT 2QB/deltoid with an insert close-up image of the deltoid spurge (C. deltoidea ssp. pinetorum), March 8, 2019 (an intensely burned area one-month post-fire).

B. LAQI WPT 42, diverse area. April 13, 2019. An area (quadrat) initially selected for its diversity of emerging shrubs, grasses, and plants (with *Lantana* in bloom); and limestone (Figure 49).

Figure 49. LAQI WPT 42, diverse area, April 13, 2019.

C. LAQI WPT 48, native Walter's ground cherry, *Physalis walterii* Nutt., September 7, 2019. This is an area of palmetto, shrubs, and exposed limestone/pine needle mix, with some grass/herbaceous ground cover mix (Figure 50).

Figure 50. LAQI WPT 48, September 7, 2019, Walter's ground cherry, *Physalis walterii* Nutt.

D. LAQI WPT 28, December 28, 2019, native Pineland croton, *Croton linearis*. Grassy and herbaceous ground cover with palmetto, shrub, and exposed limestone/pine needle mix (Figure 51).


Figure 51. LAQI WPT 28, December 28, 2019, native Pineland croton, *Croton linearis*.

E. LAQI WPT 29, February 22, 2020. The native dollarweed, *Rhynchosia reniformis*, located with orange flag: in the Redland soil area, with heavy-grass one-yr. post-fire; a mix of herbaceous plants and pine needles; and a small amount of exposed limestone, shrub, and palmetto (a small, dead pine tree trunk in the top left corner) (Figure 52).


Figure 52. LAQI WPT 29, February 22, 2020. The native dollarweed, *R. reniformis*, located with small orange flag.

The condition of individual species of the herbaceous ground cover was tracked using the LAQI quadrat imagery. Processed LAQI imagery was also used to describe and discriminate the individual PR habitat classifications and the spectral signatures of the ground cover group types. The majority of the center WPT indicators were chosen based on their identification as a characteristic or endemic PR plant species, and/or they are having a known specific ecological function in the PR ecosystem (such as *croton* and relationship as a host for butterfly species) (Figure 51). Some WPTs, such as WPT 42 (Figure 49), were used to identify the center coordinate point of a specific area that included diverse PR ground cover characteristics, such as exposed limestone, woody material, a blooming plant, and a mix of grass, herbs, ferns, and shrubs. (Refer to *Methods* Section for more information on WPT indicator selection process). A photo log was compiled of the first and last LAQI images for each of the quadrats, and the first and last cell photos of their center-WPT indicators and linked to the SEW.

Unsupervised and Supervised LAQI Image Classification:

The ArcMap image classification process was used with the single-image LAQIs for classifying the PR ground cover habitat classes. As with the flight survey image classification process, the intent was to discriminate the different ground habitat classes and to represent the existing image-diversity (pixel/class variation). The merging of pixels (colors) and the generalization of classes was minimized. Instead, as much as possible of the pixel variation (such as various shades of green color) was retained, and different group types identified, during the classification process.

Unsupervised LAQI image classification.

A detailed review of the herbaceous ground cover, often to the species level, was performed with the high-definition, t-c LAQI images. The WPT 35, wildland petunia, (*Ruellia succulenta*) LAQIs (Figure 53) are representative of the PR ground cover in the study area, Unit 2A. The diverse ground cover classes were able to be identified with the LAQI images.

The wild petunia plant (WPT 35) is identified in bloom in the July 6, 2019 LAQI image, as well as a yellow blooming lantana plant. A closeup image of the blooming petunia (WPT indictor) was produced using the LAQI image and is shown in Figure 54.

Figure 53. LAQI .jpg t-c images of LAQI WPT 35, Wildland petunia (*R*. *succulenta*). Upper: July 6, 2019 with yellow blooming Lantana, *Lantana* spp., Lower: February 22, 2020.

Figure 54. LAQI WPT 35 close-up of wildland petunia, *R. succulenta* in bloom (purple flower), July 6, 2019.

These blooms were also captured in the unsupervised classification images for these same LAQIs (Figure 55). The unsupervised classification of LAQI WPT 35 resulted in the identification of the diverse suite of PR ground cover habitat classes present in the t-c image and include shrub, palm, grasses, exposed limestone and soil, pine needles, fine wood fuels, forb ground vegetation, and the bloom of the pineland petunia (Figure 55). Further discrimination of the forb vegetation (green shades) was not possible in the processing.

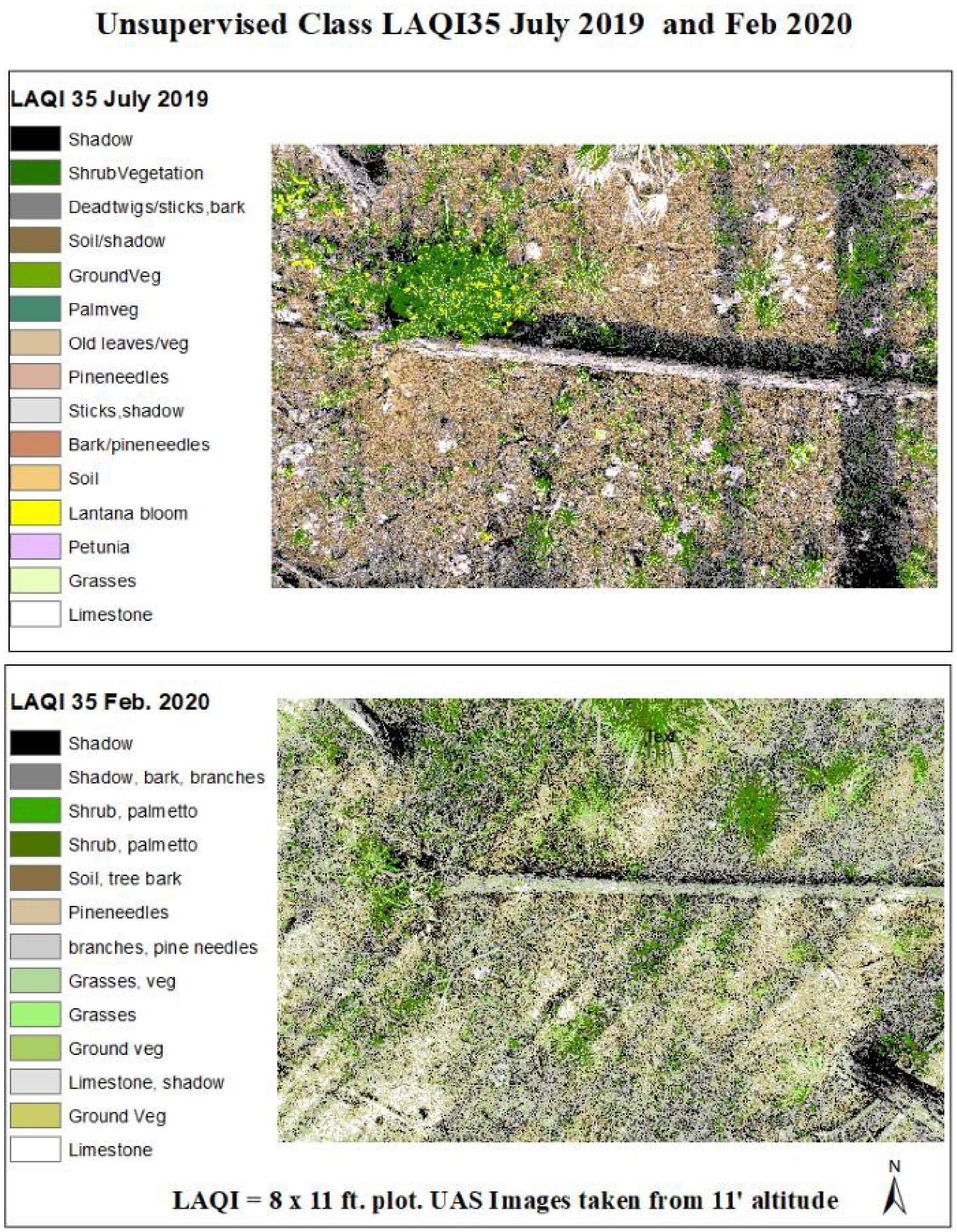


Figure 55. Unsupervised classification of LAQI 35. July 2019, and February 2020.

Differences in habitat classes identified between the July 2019 and February 2020 unsupervised LAQI WPT 35 images provide feedback on the post-fire changes to the ground vegetation (Figure 55). In the February 2020 LAQI, the petunia and lantana are no longer observed in bloom. The growth in palmetto and grasses is now noticeable, compared to the exposed soil and limestone present in the July 2019 quadrat. A summary of the unique color classifications and pixel counts for these unsupervised classifications is in Appendix 5.

The diverse ground cover identified in the LAQI, t-c and unsupervised classification images for WPT 35 LAQI (Figure 53 and Figure 55) were compared to the reduced diversity documented for the fire-suppressed and overgrown PR habitat in LAQI images of Unit 2West (also known as Unit 1), the unit directly adjacent to Unit 2A (fire site), and last burned in 2016. The t-c LAQI images in Unit 2West (LAQI1 and LAQI2) are shown in Figure 56. The unsupervised classification image of LAQI1, Unit 2West, is shown in Figure 57. The predominant classes identified at this quadrat were: “dead ground vegetation”, “dead palm fronds”, and “green palm vegetation”. The LAQI images and site visits to this unit documented dead (stagnant) vegetation overwhelming the herbaceous ground cover below. Most of the dead vegetation was still attached to the living plant and was not made of loose ground litter. The (green) live vegetation in this unit and identified in the LAQI images was almost entirely palm fronds, rather than healthy green ground cover. The overall resulting view of these Unit2West images (similar to those documented in Unit 4; Figure 36) is a brown-monotone that lacks signs of growth and complexity in the ground cover habitat compared to the LAQI WPT 35 images in the burned area of Unit 2A.

Figure 56. Overgrown PR, Unit 2West (Unit 1) Navy Wells. t-c LAQI 1 (upper) and LAQI 2 (lower), February 22, 2020.

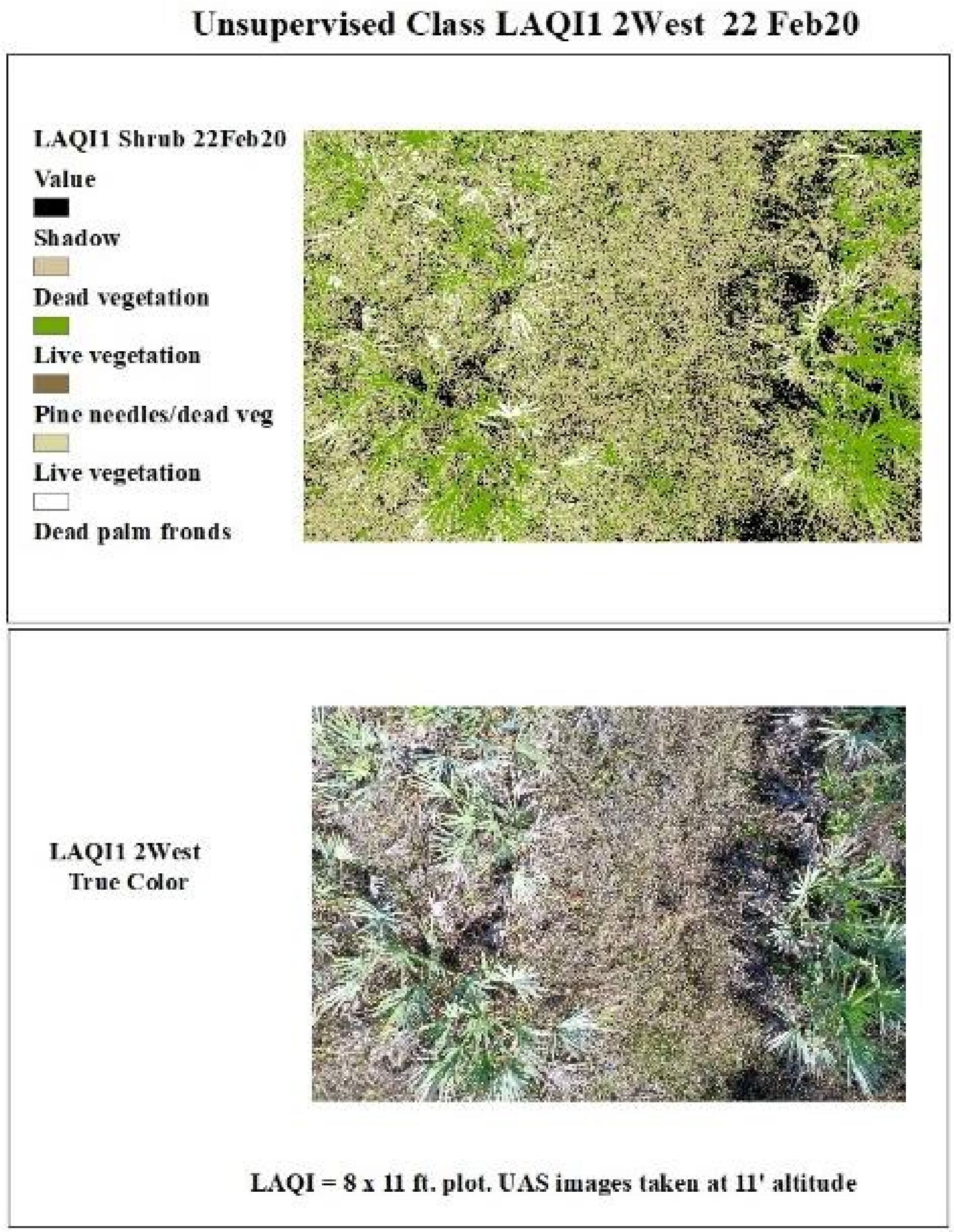


Figure 57. LAQI 1, Unit 2West (Unit 1). Unsupervised classification (upper); t-c image (lower). Overgrown grasses, old palmetto, shrubs, and dead branches.

Supervised LAQI image classification; time-series.

The supervised image classification method was used with LAQI WPT 2QA, sabal palm, in a set of three, monthly images (Figure 58). Similar to the unsupervised classification, the discrimination and separation of the ground cover class types were possible using the supervised method with these (smaller, low altitude) LAQIs. As in the larger flight survey images, similar color shades (pixel values), mainly of green vegetation, created spectral signature overlaps in the scatterplot and histogram (graph) results (Figure 59 and 60).

Habitat classes developed in the supervised classification process for LAQI WPT 2QA, include those typical to the PR ground cover: grasses, herbaceous plants, palm fronds and trunk, exposed limestone, pine needles, and light branches and twigs. The "pine needle" class was commonly identified as a predominant class type in the PR ground cover imagery. A class type for "light branches and twigs" was developed because of their important contribution as fine fuels for low-intensity surface fire considered ideal for the PR system. Graphs were created for the supervised classification images of March 8, 2019; October 5, 2019; and February 22, 2020 LAQI WPT 2QA, sabal palm.

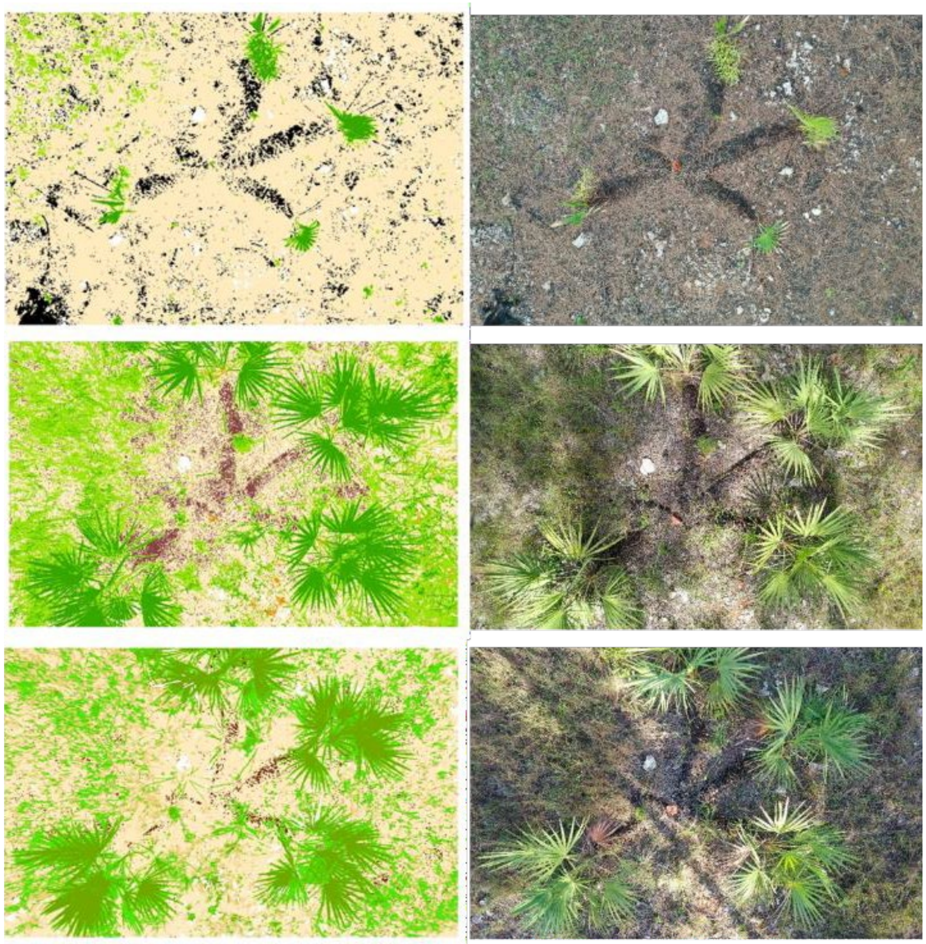


Figure 58. LAQI 2QA supervised classification (left) and t-c (right) images. Upper to lower: March 8, 2019, October 5, 2019, February 22, 2020.

The March 8, 2019 2QA LAQI histogram for "*all classes*" (Figure 59), illustrates the strength of the spectral signature in the image of the emerging palm frond vegetation (green). Pine needles, burnt vegetation (including burnt palm bark; and trunks lying horizontally on the ground) make up a large proportion of the quadrat. The spectral signature for the exposed limestone (white) is distinctly separated from the remaining ground cover signatures. The beginning growth of grass and small herbaceous ground cover in the quadrat is the histogram's small, bright green, spectral signature. Figure 59 shows the "*all classes*" training sample for the March 8, 2019 supervised images (Figure 58 upper image, and 60).

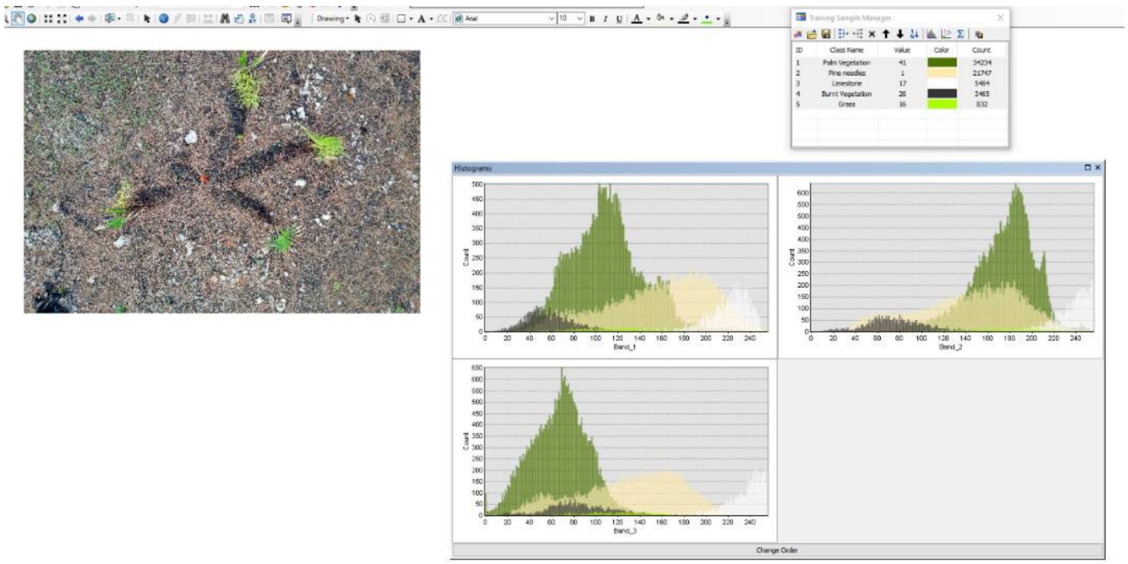


Figure 59. March 8, 2019 LAQI 2QA, sabal palm. Supervised classification image. Histogram of all ground cover classes.

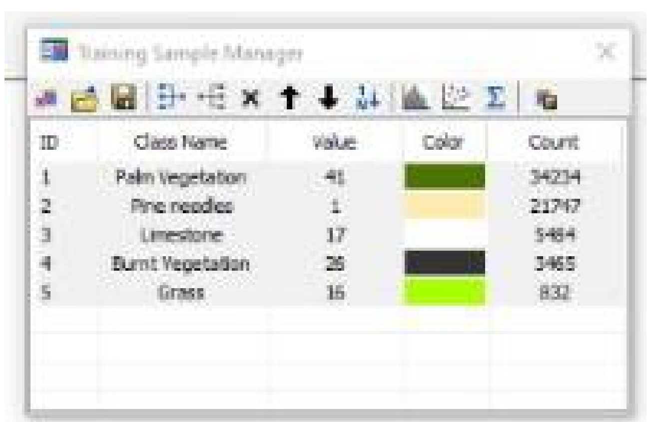


Figure 60. Closeup print screen image of Training Sample for All Classes; Supervised Classification March 8, 2019 LAQI 2QA, sabal palm.

Figure 61 is the same March 8, 2019, supervised classification image (Figure 59), with only the "pine needles" (light brown), and "green herbaceous ground cover" (small, bright green) spectral signatures shown in the histogram.

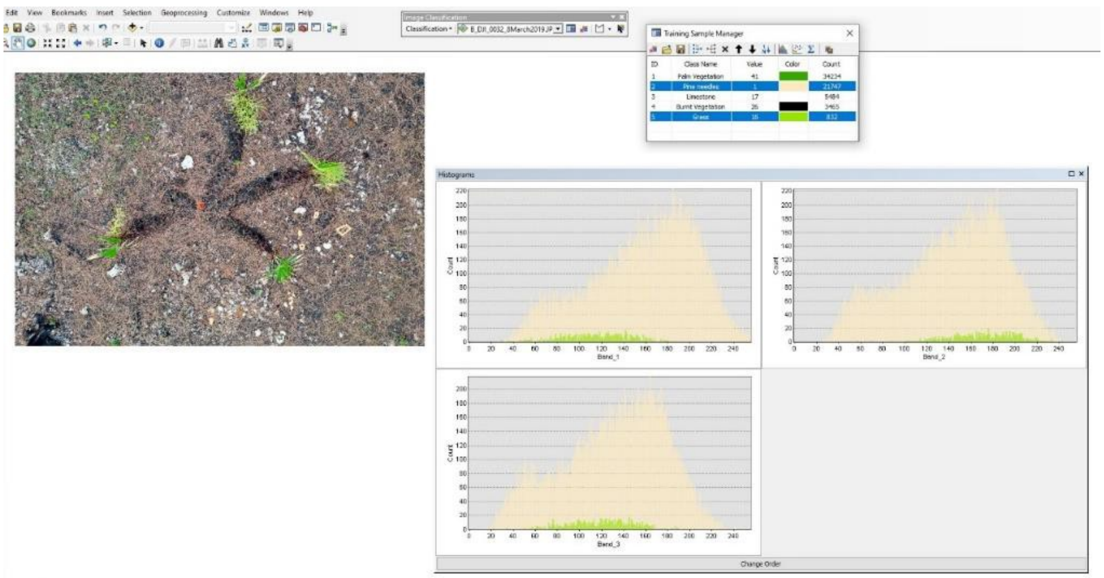


Figure 61. March 8, 2019 LAQI WPT 2QA, sabal palm. Supervised classification image. pine needles (brown) and herbaceous ground cover (bright green) spectral signatures.

The scatterplot for the October 5, 2019 image (Figure 62) consists of the following classes: "palm fronds" (green), "palm trunk" (dark brown), "grasses" (with mix of herbaceous plants) (bright green), "bare soil" (bright orange), "exposed limestone" (white), and "dead pine needles" (light brown) (the dead pine needle spectral signature is overlapped with the palm trunk and bare soil signatures) (Figure 63). The individual classes are still distinguishable in the scatterplot, but the high degree of overlap between them illustrates the amount of vegetative growth that has taken place in this quadrat since the fire.

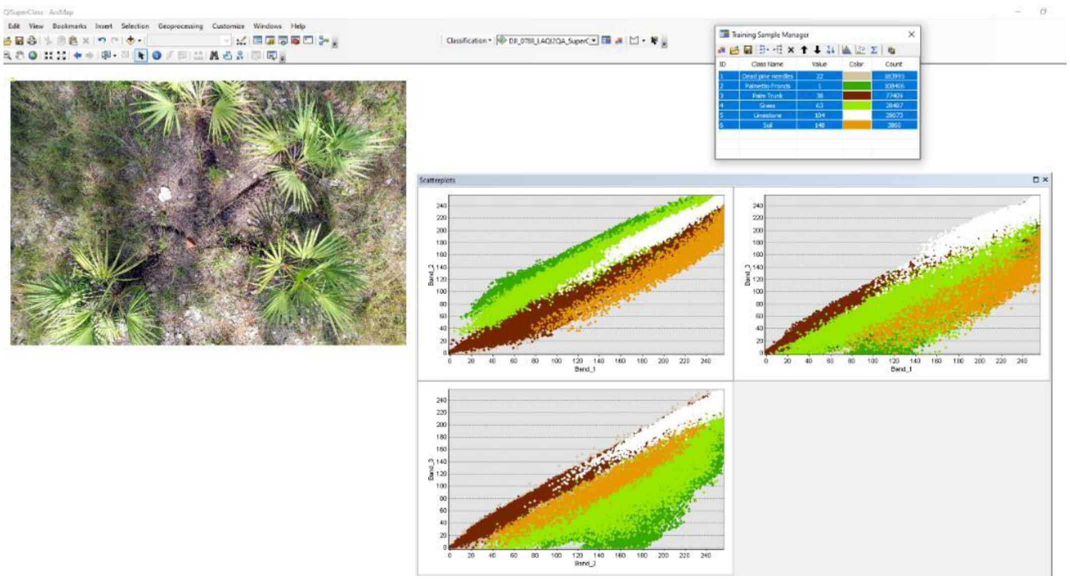


Figure 62. October 5, 2019, LAQI 2QA, sabal palm. Supervised classification image. Scatter plot of all classes.

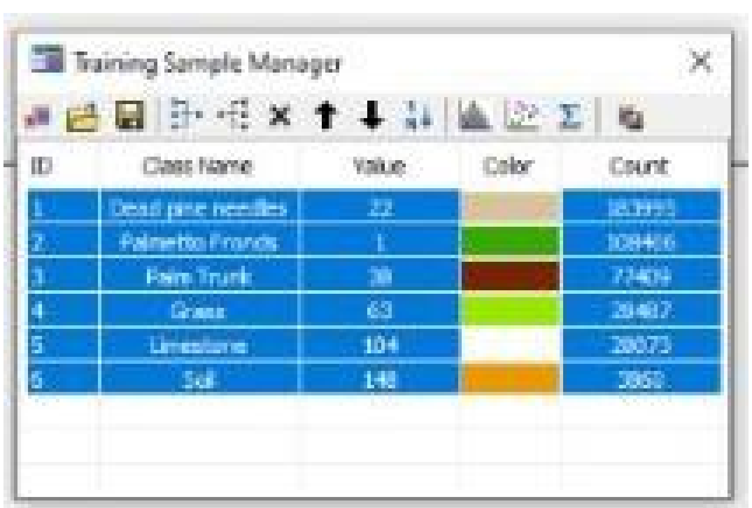


Figure 63. Closeup print screen image of Training Sample for All Classes; Supervised Classification October 5, 2019, 2019 LAQI 2QA, sabal palm.

A predominance of grassy ground cover is documented in the quadrat one-yr. post-fire. The more significant spectral signature for the "grass/herbaceous ground cover" in the February 22, 2020 histogram and scatter plots (Figure 64 and Figure 65) (with the "sabal palm" signature removed) can be compared to the representation of this same class type in the March 2019 LAQI, Figure 61. The "grass/herbaceous ground cover" is dominant in the February 22, 2020 quadrat, and the "pine needle" group continues to represent a distinct spectral signature (Figure 58, lower; 64). The training sample for the February 22, 2020 images is shown in Figure 66. The spectral signatures for the "pine needle" ground cover class, like the "dead branches/twigs" class type, can be monitored with this imagery to provide insight on available fine fuels in the PR habitat. By February 2020, the bare soil seen in the October 5, 2019 image (Figure 62) is not identified in the processing; now covered by ground cover vegetation or pine needles.

The choices to "select" or "not select" (remove) specific training sample class types for viewing the spectral signatures in the scatterplots or histograms allowed for various options to reviewing and making comparisons between the classes. The supervised classification of the diverse and complex LAQI images can be time-intensive to identify the group/class diversity in the resulting images. Still, the LAQI images are small, and can otherwise be processed quickly compared to the larger orthomosaic images. These LAQI images provided focused information on the PR herbaceous ground cover, which is a key indicator for the PR system, and where the majority of PR diversity occurs. LAQI images are relatively efficient to acquire; many images can be collected during a research site visit. They allow the researcher to focus on specific areas, such as with heavy palmetto, or exposed limestone. The smaller images provided more detailed and supportive information to the UAS flight surveys of the lower, “under the canopy,” mid-story and ground cover PR habitats.

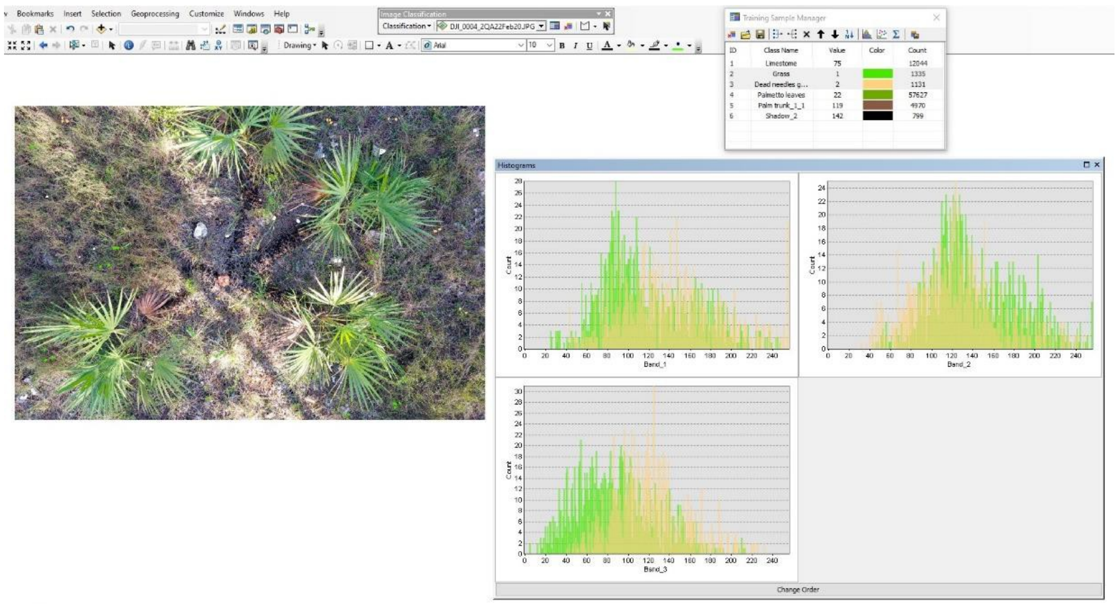


Figure 64. February 22, 2020, LAQI 2QA, sabal palm. Supervised image histogram of grass (green), and pine needles (tan) spectral signatures only.

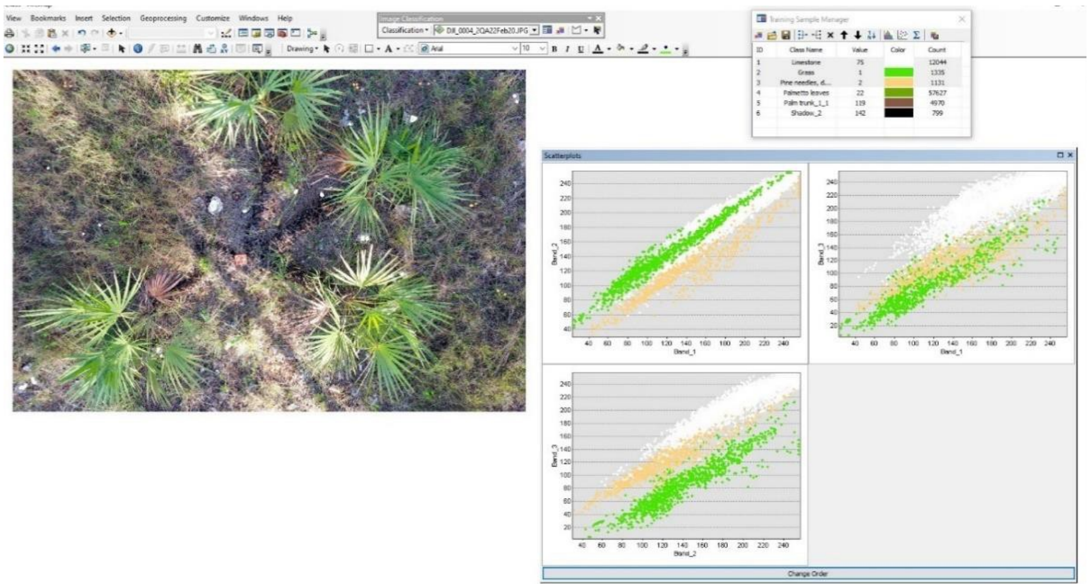
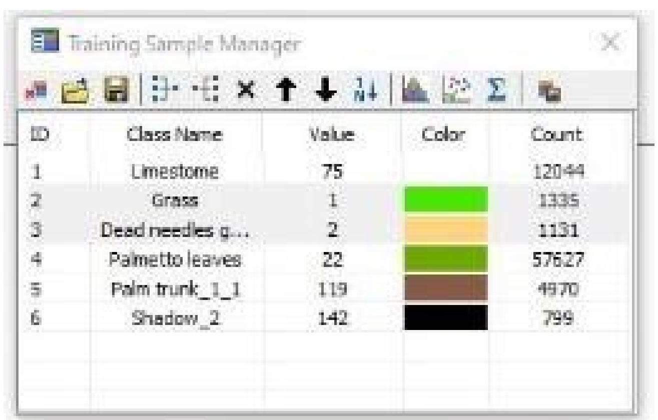


Figure 65. February 22, 2020, LAQI 2QA, sabal palm. Supervised classification image. Scatter plot of grass (green), limestone (white), and pine needles (tan) only.


Training Sample Manager

ID	Class Name	Value	Color	Count
1	Limestome	75		12044
2	Grass	1		1335
3	Dead needles g...	2		1131
4	Palmetto leaves	22		57627
5	Palm trunk_1_1	119		4970
6	Shadow_2	142		799

Figure 66. Closeup print screen image of Training Sample for All Classes; Supervised Classification February 22, 2020 LAQI 2QA, sabal palm.

A summary of the PR below-canopy ground cover types with their spectral signature descriptions identified from the LAQI classification images is provided in Table 5. Choice in class colors was a subjective step during the classification process.

The processor made an effort to select colors accurate to the t-c image being used.

Table 5. PR image classification, below-canopy ground cover habitat types.

Habitat Types
Pine tree (s) (brown, brown/gray bark and trunk)
Exposed Limestone (white)
Limestone/mix with pine needles (needles/with visible limestone) (brown/mauve with white mottled mix)
Pine needles (brown/mauve)
Grasses (make note of dead vegetation on grasses and shrubs but not loose on ground) (green; greenish brown)
Herbaceous ground cover (forbs) (small green, irregular patches)
Palmettos (bluish green; unique pointed frond pattern)
Ferns (green; unique pattern)
Shrubs (woody) (green, irregular pattern; larger than ground vegetation)
Dead logs, branches (light gray; irregular narrow patterns)
Burnt ground (charcoal) (black)
Burnt pine needles (dark brown; orange)
burnt logs, branches (black; narrow pattern)

LAQI WPT imagery time-series:

Stages of grass and shrub emergence and other habitat trends were tracked comparing a set of time-series LAQI images (as in Figure 58). Further examples of LAQI time-series images are shown in Figure 67, for LAQI WPT 2QA, sabal palm; and Figure 68, for LAQI WPT 20, Locust Berry.

Pine needles are seen to dominate in the initial LAQI WPT 2QA, taken February 24, 2019, three-weeks post-fire (Figure 67). The white PVC pipe seen in this first image was used in testing standard quadrat sizes. A LAQI time-series portfolio for WPT 20, Locust Berry, is in Figure 68. The locust berry (marked by an orange flag), is an important shrub plant in the PR habitat, known to be used by numerous insects, including wasps and butterflies.

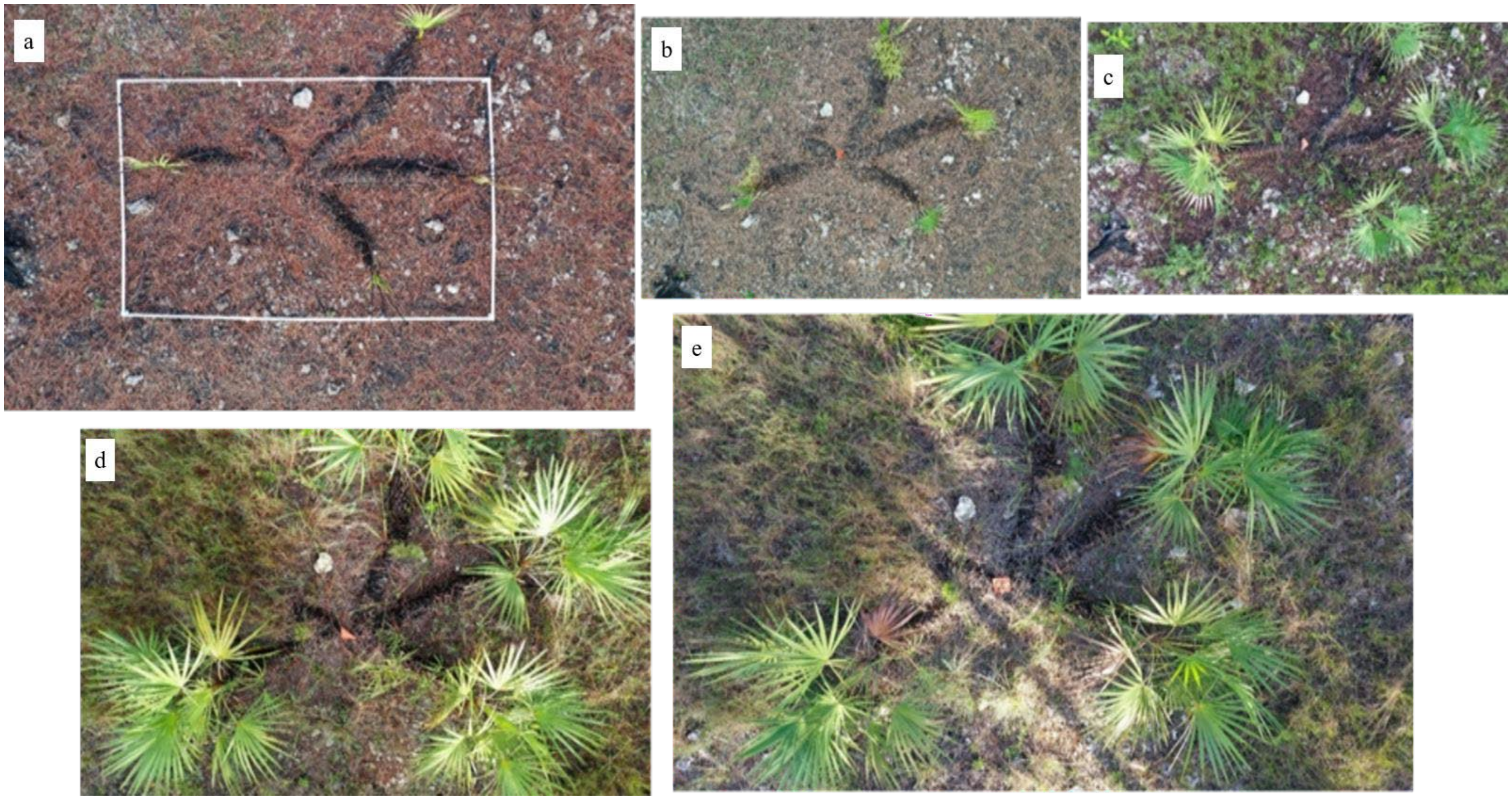


Figure 67. Time series LAQI 2QA, sabal palm: a) February 24 2019, b) March 8, 2019 c) July 6, 2019 d) Nov. 30, 2019, and e) February 22, 2020.

Figure 68. Example of a time series portfolio for LAQI WPT 20, locust berry (marked with orange flag).

Individual species (indicators in the LAQIs):

Close-up LAQI images were used to identify and examine individual PR species. The high definition, resolution, and ease of collection of LAQIs allow for excellent tracking of individual plants health. Figure 69 consists of close-up images acquired in April and July, 2019, of individual LAQI WPT35, wildland petunia (July image also shown in Figure 54).

a) April 13, 2019 WPT 35 indicator. Wildland petunia.

b) July 6, 2019 WPT 35 indicator, with bloom, (purple flower).

Figure 69. LAQI close-up images of single species WPT 35, wildland petunia, *R. succulenta*. April 2019 (upper) and July 2019 in bloom (lower).

Examples of indicators and endemic PR plant species follow in Figures 70 through 72. Figure 70 is WPT 28, croton (*c. linearis*), the primary food for larvae of endangered FL leafwing (*Anaea troglodyte floridalis*), and Bartram's scrub hairstreak butterflies (*S. acis bartrami*) (Austin 2015). The passion vine (*Passiflora suberosa*), passion vine, is known as an important food source to Longwing (*Heliconiini*) butterfly larvae (Figure 71). Figure 72 tracks the growth and bloom of WPT 34, horrible thistle (*C. horrigulum*).

Figure 70. LAQI WPT 28, croton (*c. linearis*), March 16, 2019. Close-up and cropped LAQI image.

Figure 71. LAQI WPT 34, March 16, 2019. Passion vine (*P. suberosa*) indicator (Insert).

Figure 72. LAQI WPT 44 horrible thistle (*C. horrigulum*). Growth and bloom post-fire. April 13, 2109; September 7, 2019, and February 22, 2020 (blooming).

The LAQI WPT 31, the diminutive, endemic pineland milkpea (*Galactia pinetorum*) (Figure 73), was documented in bloom in this quadrat's initial LAQI images, acquired on March 16, 2019, and July 27, 2019 (image lightened and sharpened to highlight purple bloom) (Figure 73; upper images). The abundant and widely-dispersed grasses and white-tope sedge (*Dichromena floridensis*), are seen to dominate at this exact location in the October 5, 2019, and February 22, 2020 LAQI 31 surveys (Figure 73; lower images). Close-up views of a blooming pineland milkpea and white-top sedge are shown in Figure 74 and 75, respectively.

The LAQI imagery was found to have multiple uses in the PR habitat assessment, including a) standard quadrat tracking, b) image classification of PR ground cover habitat types, and c) the examination of individual species. Other uses were in providing supplemental information to or in conjunction with, the in-field quadrat assessments to describe an estimated abundance of ground cover habitat.

Figure 73. LAQI WPT 31. Endemic *Galactia pinetorum* (Small's milkpea). Clockwise from top left: March 16, July 27, 2019, October 5, 2019 and February 22, 2020. Red arrows point to blooms. White top-sedge in lower images.

Figure 74. *G. pinetorum* (Small's milkpea) in bloom. March 16, 2019 cell photo, LAQI WPT 31.

Figure 75. White-top sedge in bloom. April 13, 2019 cell photo. Navy Wells study site.

In-Field PR Ground Cover Abundance Assessments

Initial site visits.

An initial site-visit to Navy Wells occurred on January 11, 2019, accompanied by the M-D County land manager. This visit was a preliminary inspection of the entire Navy Wells Preserve. Trial UAS flights were flown in Units 6, 7 and 4 on January 17, 2019. The arson wildfire in Unit 2 took place on February 2, 2019. An initial walk-through and visual inspection (with field notes and photos) of the Unit 2 fire footprint (Unit2A and Unit 2B), and the first UAS flights, occurred on February 16, 2019. New growth (sprouting) of palm, herbaceous ground cover, and grasses (sprouting) was identified in those first aerial images acquired of the burned area, twelve days post-fire (Figure 26). Monthly LAQI flights for Unit 2A began on February 24, 2019, 22 days post-fire, and documented the emergence of forbs, grasses, and shrubs from the burnt ground surface and limestone substrate (Figure 76).

Figure 76. First LAQI images (test image; WPT 2QB) with quadrat being measured February 22, 2019; 22 days post-fire.

A Unit 2A site inspection (walk-through) took place on March 8, 2019 (5 weeks post-fire) with the PI accompanied by botanist and PR expert J. Possley, and PR land manager and expert, S. Thompson. Each of these field visits assisted in establishing the specific indicators and quadrat center WPTs used for the LAQI and field quadrat assessments. Early post-fire, emergent growth is documented in the March 16, 2019 image of LAQI WPT 22 (Figure 77).


Figure 77. LAQI WPT 22, March 16, 2019. Ground cover habitat type can be distinguished, and separated in the image classification process.

The changes in the new, post-fire growth of ferns, palmetto, shrubs, and flowering plants are documented in the comparison between the March 25, 2019, and May 25, 2019 LAQI images and through the in-field verifications (Figure 78). By May 25, 2019, the LAQI WPT 34 images document the increase abundance of grasses, shrub seedlings, and some ground vegetation. However, the burnt, open ground, and exposed limestone were still a dominant characteristic of this quadrat (Figure 78).

In Figure 78, the low-profile, Pineland deltoid spurge, *C. deltoidea* ssp. *Pinetorum*, and a blooming Pineland allamanda (*Angadenia berteroi* (yellow bloom), are located in the May 25, 2019 image (located between the palmetto at the top of the image and the orange WPT indicator flag). A LAQI close-up image of these plants is in Figure 79.

Figure 78. March 25, 2019 (upper); and May 25, 2019 (lower) LAQI WPT 34.

Figure 79. LAQI close-up of Pineland allamanda (*Angadenia berteroi)* flower, and Pineland deltoid spurge (*C. deltoidea* ssp. P*inetorum*) in limestone. LAQI WPT 34, May 25, 2019.

Similar to the forb species, the emergent growth of shrub species was observed early, within weeks, post-fire. This initial growth occurred from the base of the unvegetated (burnt/dead) shrub branches, prior to new shoot, branch, or leaf growth; and contributed to the initial spectral signature for ground cover vegetation (Figure 80).

Figure 80. Early post-fire growth, emerging at base of shrub unvegetated branches. March 16, 2019; cell photo.

In-field Quadrat Assessment Results and Comparisons with LAQIs

In-field quadrat abundance estimates were completed on the same day as the LAQI flights, using the In-Field Quadrat Assessment Worksheet (Figure 23). The main PR habitat vegetation classification groups listed on the Worksheet, and identified in the classification of the LAQI images, were assessed (Figure 23; Table 5). The In-field abundance estimates were completed following the methods described in the Methods Section, "*In-Field Quadrat* Assessments". Cell photos of each quadrat, as well as a close-up photo of that quadrat's flagged center-WPT indicator, were taken when LAQI flights and in-field estimates were completed, and a sketch or schematic was completed with the abundance estimates to provide supplemental information. The worksheet information was later transferred to an Excel spreadsheet part of the SEW used for this research. An example Excel spreadsheet for October 2019 through February 9, 2020 assessment results is in Appendix 7.

A proof-of-concept exercise was completed to compare results between the in-field quadrat percent abundance estimates, and the results found when using the same assessment process with LAQI images. The purpose was to examine the extent to which LAQI images could be used to discriminate the PR ground cover types and abundance. The PI did all of the field assessments, but other individuals completed assessments of the LAQI images during this exercise.

Using the same worksheet and methods used with the in-field quadrat assessments, individual .jpg LAQI images were provided to outside reviewers knowledgeable to PR habitat, to assess the estimated ground cover-abundance of that quadrat using the LAQI image. Two individual LAQI images each, were sent to three outside reviewers. Instructions were given to those individuals who assessed the individual LAQIs, to take no more than 15 to 20 minutes to complete the LAQI assessment; the same amount of time given to complete a single in-field quadrat assessment. They were instructed that it was possible to use the zoom in or view the image close-up to the degree preferred, and while not necessary as part of this assessment, to document single species, if identifiable in the image.

The results of the LAQI image assessments were compared to the "sister" in-field quadrat assessment completed by the PI (on the same day the LAQI image was acquired). The LAQIs assessed by the outside reviewers include October 5, 2019 LAQI WPT 20 and WPT 44 (Figure 81); November 2, 2019 LAQI WPT 48, and December 28, 2019 WPT 16 (Figure 82); and December 28, 2019 WPT 32 and WPT 56 (Figure 83). The PI selected these images for their diversity and abundance of PR habitat characteristics to test the ability to discriminate habitat types in diverse ground cover. The results of these six comparisons are presented in the Table 6.

WPT LAQI 20, locust berry, October 5, 2019 (upper image).
WPT LAQI 44, thistle, October 5, 2019 (lower image).

Figure 81. October 5, 2019 LAQIs used for comparison to in-field assessment.

WPT LAQI 48, Walter's ground cherry, November 2, 2019 (upper image). WPT LAQI 16, Ipomea, December 28, 2019 (lower image).

Figure 82. November 2, and December 28, 2019 LAQIs used for comparison to in-field assessment.

WPT LAQI 32, Lantana, December 28, 2019 (upper image).
WPT LAQI 56, Angalina, December 28, 2019 (lower image).

Figure 83. December 28, 2019 LAQIs used for comparison to in-field assessment.

Table 6. Comparison between quadrat field assessments and LAQI reviews

	Field assessment date: 10/5/2019	**LAQI Review**	**Field assessment date: 10/5/2019**	**LAQI Review**
Waypoint (WPT)	**20**	**20**	**44**	**44**
WPT AKA	**locust berry**	**locust berry**	**thistle**	**thistle**
Ground Cover Type	**Estimated percent abundance***	**Estimated percent abundance**	**Estimated percent abundance**	**Estimated percent abundance**
Pine tree (s)			5	1-5
Limestone	10	25	55	5-25
Limestone/mix with pine needles (needles/with visible limestone)	10	10		5-25
Pine needles	5	5	15	25-50
Grasses (make note dead vegetation on grasses and shrubs but not loose on ground)	30	20		0-1
Herbaceous ground cover (forbs)	20	15	5	5-25
Mixes of grasses and plants (forbs)				
Palmettos			5	0-1
Ferns	5	4	5	1-5
Shrubs (woody)	15	20	10	5-25
Dead logs, branches (unburnt)	5	1		0-1
Burnt ground (charcoal)				0-1
Burnt pine needles				0-1
Burnt logs, branches				0-1

* Empty cell denotes <1%.

Table 6. cont'd.

	Field assessment date: 11/2/2019	LAQI Review	Field assessment date: 12/28/2019	LAQI Review
Waypoint (WPT)	**48**	**48**	**16**	**16**
WPT AKA	**Walter's ground cherry**	**Walter's ground cherry**	**Ipomea**	**Ipomea**
Ground Cover Type	**Estimated percent abundance***	**Estimated percent abundance**	**Estimated percent abundance**	**Estimated percent abundance**
Pine tree (s)-live trunk/roots	overlooked trunk	1-5%		0-1
Limestone	0-1	10	5	1-5
Limestone/mix with pine needles (needles/with visible limestone)	55	20		0-1
Pine needles	0-1	30		1-5
Grasses (make note dead vegetation on grasses and shrubs but not loose on ground)	20	10	85	25-50
Herbaceous ground cover (forbs)	15	5	5	1-5
Mixes of grasses and plants (forbs)		15		25-50
Palmettos			5	5-25
Ferns				0-1
Shrubs (woody)	10	5		1-5
Dead logs, branches (unburnt)		0-1%		0-1
Burnt ground (charcoal)				0-1
Burnt pine needles				0-1
Burnt logs, branches				1-5

* Empty cell denotes <1%.

Table 6. cont'd.

	Field assessment date: 12/28/19	LAQI Review	Field assessment date: 12/28/19	LAQI Review
Waypoint (WPT)	**32**	**32**	**56**	**56**
WPT AKA	**Lantana**	**Lantana**	**Agalinis**	**Agalinis**
Ground Cover Type	**Estimated percent abundance***	**Estimated percent abundance**	**Estimated percent abundance**	**Estimated percent abundance**
Pine tree (s)- live trunk/roots				5
Limestone	5			
Limestone/mix with pine needles (needles/with visible limestone)		15	50	60
Pine needles	35	30		
Grasses (make note of dead vegetation on grasses and shrubs but not loose on ground)	45	30		3
Herbaceous ground cover (forbs)	10	5	10	15
Mixes of grasses and plants (forbs)			10	
Palmettos	5	10	10	10
Ferns		5		
Shrubs (woody)			20	
Dead logs, branches (unburnt)				4
Burnt ground (charcoal)				
Burnt pine needles				
Burnt logs, branches		5		3

* Empty cell denotes <1%.

Each of the LAQI images and in-field quadrat assessments contributed specific information in the discrimination and assessment of the PR herbaceous ground cover. LAQI images were used to supplement or clarify the in-field assessments, and the in-field assessment results were used to assist in cross-checking specific habitat group types in the review of individual LAQI images and during the image classification process. These products became most effective when used in a complementary fashion with the additional resources compiled in this research.

Specific, individual habitat group types including "exposed limestone," "forbs," "grass," and "pine needles" were able to be well-discriminated and separated from one another in the evaluation of early post-fire images in both the LAQIs (Figure 76), and in-field quadrat assessments. Before the return of herbaceous vegetation, the ground cover in these early images consisted of "exposed limestone" or "burnt and charred ash of pine needles with ground vegetation" Any vegetation present was that of sparse, newly-emerging sprouts.

As the abundance and density of the ground cover vegetation returned to the site, the ability to visually separate the individual group types became more challenging in the in-field assessments. Areas of the PR ground cover and estimated abundances were then more accurately identified as "mixed" habitat, including "limestone/pine needle mix" and the "grass and forbs mix" (Figure 23). The time and effort needed to complete the assessments increased slightly with the increase in species richness and the return of the ground cover mosaic. As mentioned, to test the ability to discriminate habitat types in diverse ground cover, LAQI images acquired later in the yr., (October 2019 to February,

2020) after the vegetation had returned to the site were used in this comparative exercise (Table 6).

This “mix” of habitat types and the mosaic nature of the ground cover identified in the in-field and LAQI quadrat assessments were also reflected in the results of the supervised classification images and the partial overlap found between similar spectral signatures of different habitat types. Images became more complex (“messier”) with the mix of the small forbs and grasses, the accumulation of pine needles over exposed limestone, and the growth of the midstory shrubs post-fire. The “dead logs, branches” and burnt materials group types were included in the field abundance estimates to provide information on available fine fuels and their contribution to the structural complexity of the PR ground cover.

The estimated percent abundances for single, monotypic habitat types such as “exposed limestone,” “grass,” “herbaceous forbs,” and “pine needles” were often found not to be equivalent between the in-field assessment and LAQI review results. Although the estimates were often reported within a similar range, there was still an overall high degree of variability in the estimated values between the two assessment methods for a given habitat type.

However, the combined (percent abundance) estimates for related groups (mixed habitat types) were often comparatively similar or equivalent when comparing the results of the two assessments. For example, although the results of a LAQI review for WPT 48, November 2, 2019, recorded the percentages 10%, 30%, and 20%, for the “exposed limestone,” “pine needles,” and “limestone/pine needles mix” group types, respectively (totaling 60%), the in-field assessment recorded a total of 55% for the" limestone/pine needle mix" group, and just 0-1% for the individual, "exposed limestone" and "pine needle" groups. Therefore, a similar proportion of "limestone" and "pine needle" were reported (55% versus 60%) in each of the assessments [with one assessment (the LAQI review) reporting individual habitat types, and the in-field assessment reporting as "mixed" habitat types].

Differences were also found in the comparison between the two assessment methods in the reported estimated percent ratio of the "grass," and "herbaceous forbs," versus the "mix of grass and forbs" group types. Again, the comparison of the estimates of these individual groups showed a high level of variability. Still, the combined total estimated percent of these related groups were similar between the two estimates. For example, when these groups were compiled. For WPT 56, December 28, 2019, the LAQI evaluator recorded 3% "grasses," and 15% "herbaceous forbs," (no percentage of grass/forbs mix recorded). The in-field assessment of this same WPT 55, quadrat recorded 10% "herbaceous ground cover (forbs)," and 10% "mix of grasses and forbs" (Table 6). The LAQI review estimated an 18% abundance for "grass" and "herbaceous forbs" combined (total of both % classes), and the in-field assessment estimated a 20% abundance of "grass/forbs mix."

One reason for the variability in reporting between the two methods was that the (PI's) in-field assessments were obtained from the ground-level perspective. The LAQIs' nadir (downward) view may have afforded a perspective to visually more accurately separate groups such as the "exposed limestone" and "pine needles." Individual variation in the interpretation of group type, and the tendency to merge versus split groups were also likely contributors to discrepancies between results. The PI performing the in-field assessments tended to identify “mixed” habitat groups more often than individual habitat types once species richness and abundance returned to the quadrats.

One of the more substantial discrepancies found in the comparison of results between the two methods was in WPT 56; December 28, 2019 (Table 6; Figure 83) in which the in-field evaluation recorded 20% shrubs, but the LAQI evaluator did not record any presence of shrubs. All other habitat group types reported between these evaluations were relatively similarly. The discrepancy may have been an omission by the LAQI evaluator. Or, what the field evaluator (PI) observed and recorded as “shrubs” (small emerging shrubs), the LAQI reviewer perceived to be “herbaceous ground cover” (forbs) based on the nadir perspective of the LAQI image. From the view above, it was possible that small shrub vegetation could be perceived as herbaceous (plant) vegetation. One LAQI evaluator inquired how to best categorize “woody shrub seedlings,” therefore the discrepancy may have been due to a lack of specific instructions. In the worksheet (Figure 23), the instructions intended the reviewers to consider woody “shrubs” (and shrub seedings) separately from the nonwoody “herbaceous ground layer” plants (forbs) but this was not specifically explained in the instructions.

The comparison of results also highlighted the differences in the appearance of habitat groups between the ground-level (in-field) view to the nadir/straight down view of the LAQIs. The LAQIs appeared to provide clearer discrimination of the small ferns, shrubs and grasses than the ground-level view. The downward view of the LAQI also appeared to estimate exposed limestone better. While some practice by the reviewer was needed to become accustom to this nadir vantage point, the “exposed limestone” could visually be discriminated from the “limestone/pine needles mix” with greater accuracy than from the ground-level view. However, the LAQI evaluation tended to underestimate the small forbs as an individual group (more often recording them within the “grass/forbs mix” group). In the field, the small forbs could be better discriminated against or separated visually from “grasses” than with the LAQI images.

A disadvantage of the LAQI review was a loss of depth perception compared to a three-dimensional view provided on sight. The reflection or “brightness” in a LAQI image sometimes made it more difficult to clearly discriminate an area of the quadrat. It was possible to use the other LAQIs (taken during same flight session but at different altitudes) to assist with specific areas.

Variability occurred in how evaluators reported estimated ranges. Some evaluators used the ranges (as example, 50-75%) as presented in the instruction. Others more specifically used a single, estimated percent abundance (such as 55%, within the range of 50-75%), and others used both methods. The comparative results can be attributed to differences in evaluator-experience in interpreting PR habitat, particularly in the LAQI images. The nadir (downward) view required some practice/experience to be able to interpret landscape details and habitat groups. Still, with the high definition and small scale of the LAQI images, and the familiarity of the habitat by the reviewers, the nadir image was a minimal issue once reviewers became accustomed to the viewpoint.

Differences between the assessors' fields of expertise played a role in the results (such as a different viewpoint that a fire ecologist may have compared to a botanist).

Ad hoc imagery results

Flight log summary

A total of fifty-five (55) ad hoc flights were flown between February 24, 2019 and February 9, 2020. Ad hoc flights were flown in-conjunction with the in-field research days when LAQI flights and in-field quadrat assessments were completed. Ad hoc flights, like LAQIs, were flown manually, under-the-canopy. The pilot would visually plan the flight prior to TO, considering the UAS flight path and the route the pilot would take in stepping through the area while piloting the UAS. Between 20 to 200 images were collected during a single ad hoc flight, with most flights consisting of approximately 50 to 120 images.

All results presented in this research are from adhocs flown using an automatic 5-second photo capture, and manual stop-and-start flight at an 11' altitude (altitude consistent with LAQI WPT images). The UAS flight mode was set to "Sport" for most of the ad hoc flights so the front-collision-avoidance measures (automatic braking and alarm) were turned off to support maneuverability of the UAS at low altitude around the pine trees. During flights in which the UAS was not set on "Sport" flight mode, the UAS' automatic front-obstacle-avoidance braking (that would occur when flying through narrow spaces between trees) was overcome by flying the UAS laterally, with its left or right side leading, until the UAS was away from the obstacle(s).

Ad hoc images.

The resulting georeferenced, .jpg images were processed into orthomosaic and VARI imagery in Agisoft, using a similar workflow for the UAS flight surveys. The VARI raster calculator was processed on a total of 11 ad hoc orthomosaics, and image classification rasters were developed in ArcMap with selected ad hoc orthomosaics. The processed ad hoc orthomosaics consist of between were 34 to 170 aligned images. The smallest (approximately 130 sq. m [1400 sq. ft]) "snapshot" ad hoc orthomosaic, developed with only 34 images, is shown in Figure 84.

Figure 84. Ad hoc orthomosaic July 6, 2019; Unit 2A, developed with 34 .jpg images; approximately 130 sq. m (1400 sq. ft).

The orthomosaic of the first under-the-canopy ad hoc flight, flown on April 13, 2019 over the Redland soil area in Unit 2A, resulted in the high-resolution snapshot (postcard image) of the PR ground cover (Figure 85). The April 13, 2019 ad hoc

Figure 85. April 13, 2019, Orthomosaic (unedited) of first ad hoc flight, Unit 2A, Redland soil area.

flight consisted of a total of 140 acquired images; 118 aligned in the processing. The partial lack of image alignment during processing was due to the inadequate overlap of some images during flight, resulting in two orthomosaic images. These ad hoc images provided highly-detailed, unobstructed views of the PR ground cover. In Figure 85, the beginning of the post-fire recovery of grasses, forbs, and shrubs can be seen; exposed soil and limestone, ash, and dead logs are still visible. The orange semi-circle item on the left side of the smaller image is the UAS TO pad. These smaller "snapshots" were easy to acquire and process and were used to focus on specific areas of interest, such as the Redland soil/grassy area in Unit 2A (Figure 85 and Figure 86). The image size of the ad hoc images (total number of images used to process the orthomosaic), compared to the UAS flight surveys, made them easy to work with in software programs and as illustrations for sharing. Two ad hoc flights consecutively flown and with overlapping images were aligned and batched into a single orthomosaic image of the ground cover (Figure 86 and Figure 87).

Figure 86. Adhoc. Dec.,28, 2019. Two batched flights (137 images). Under-the-canopy stand-alone “postcard” of the ground cover.

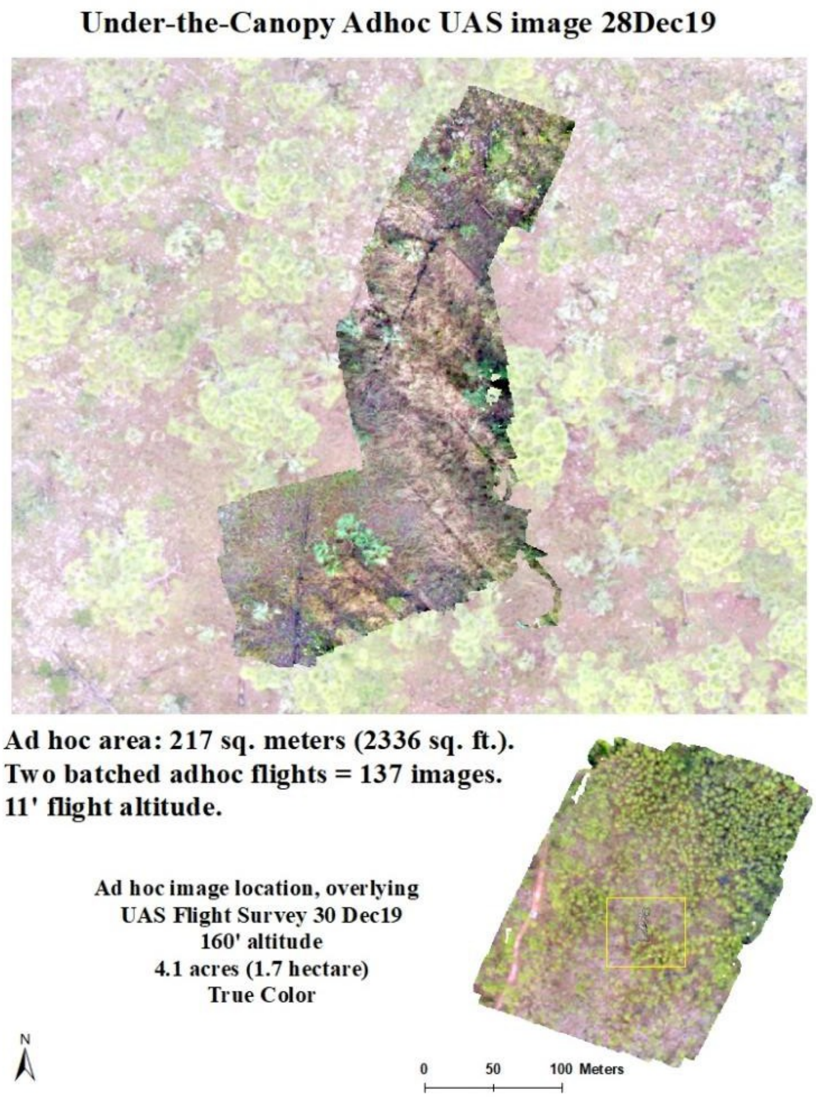


Figure 87. Ad hoc Dec. 28, 2019. Two batched flights (137 images) (adhocs 1 and 2).

Close-up examinations of ad hoc images (using ArcMap, Adobe Photoshop Editor, or Photo image software) were used to study distinct areas. In the software, images can be zoomed-in for further review and analysis. Figure 88 illustrates the close-up views of ad hoc images for April 13, 2019, and December 28, 2019, from the exact location, 8-months apart (the December ad hoc is one of the two used to create Figure 87). Note in Figure 88, the distinct burnt pine log, for reference.

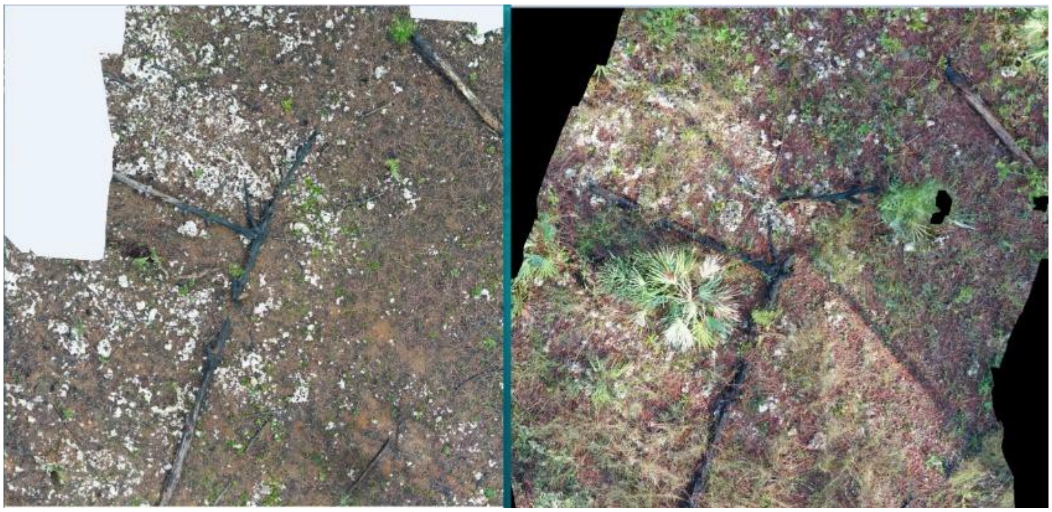


Figure 88. Ad hoc images; screen shot comparing same area between April 13, 2019 and December 28, 2019 (from Figure 86 and 87); post-fire images of grassy area.

Comparisons between the images in Figure 88 illustrated the increase of grasses (mostly gamma grass and wiregrass) by December, compared to the exposed limestone seen in the April image. Also visible are the increased growth of palmetto and the herbaceous ground cover. Some plant turnover can be seen with close-up analysis of these images. For example, note at the top, right-edge of the images, the loss of the plant from the April to December image. Comparative cell photos taken during the similar April and December time periods and locations of both ad hoc flights are in Figure 89.

Figure 89. Cell photos Redland soil area a) April 13, 2019; b) November 30, 2019.

The ad hoc images were highly effective for the focused, rapid review of specific areas and plants in the site, such as the areas of heavy grass, or abundant palmetto, for verifying ground cover classifications and comparing the condition of the PR ground cover from one point in time to another. Ad hoc flights were used to capture specific images of grassy areas, exposed limestone, shrubs, palmetto, and herbaceous forbs as well as areas of mixed diversity ground cover.

Similar to the flight survey orthomosaic images, the ad hoc orthomosaic images were also processed with the VARI raster calculator, and the two images were used together to help categorize the spectral representation of PR habitat types. Figure 90 is the t-c orthomosaic and the automatically calculated VARI raster for a September 7, 2019 ad hoc flight. In the VARI raster, the tops of the higher shrub are easily distinguished by bright red; the mid-story vegetation consisting of palmetto and shrub is seen as bright green and yellow color. In this heat palette, lower ground cover vegetation is represented by various shades of blue: exposed limestone is dark blue, and the ground cover of pine needles, grasses and forbs is a lighter shade of blue. In the orthomosaic images, palms tended to have distinct leaf shape and a light blue/aqua color; exposed limestone was white; pine needles often had a brownish/orange (mauve) tone; and hardwood shrubs were often represented by a dark brown tone. A "spectral key" for PR habitat types was ultimately developed from the imagery results to classify and assess growth or shifts in PR habitat (Table 5).

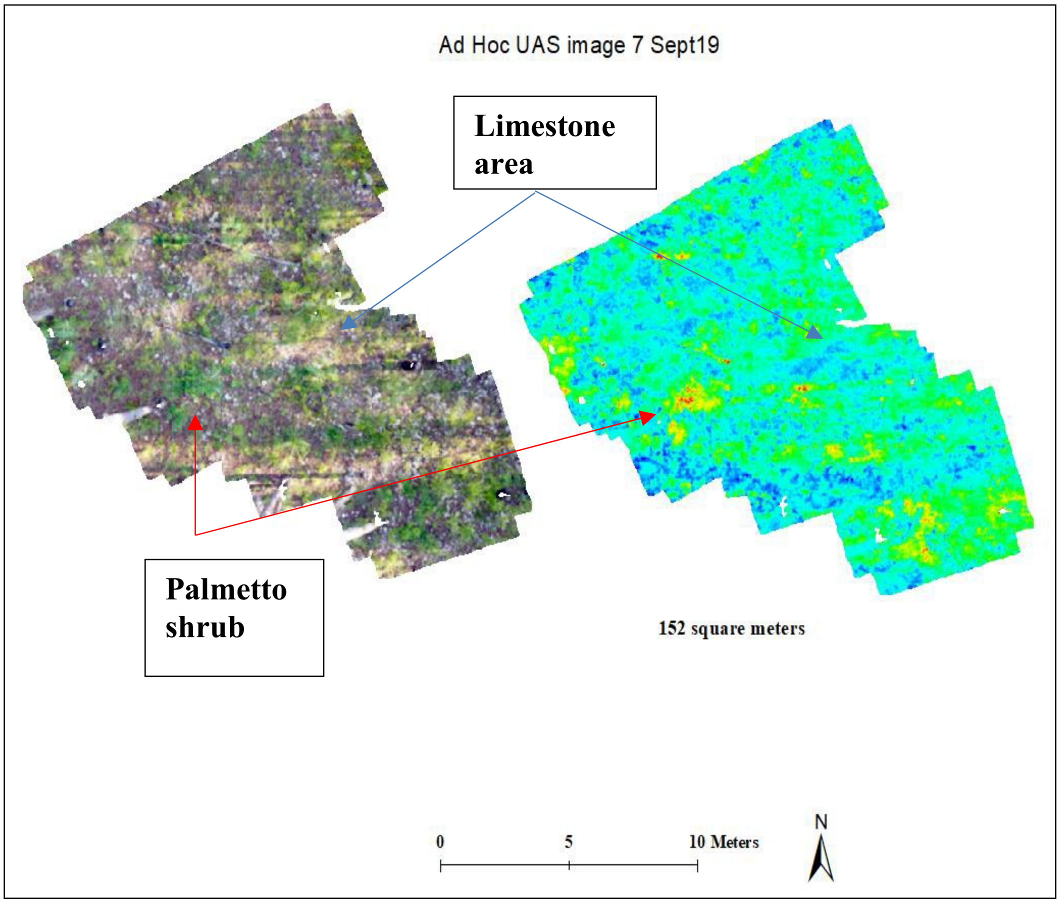


Figure 90. Ad hoc orthomosaic and VARI Auto, heat palette images. Unit 2A, September 7, 2019. 152 sq m (1636 sq ft).

Ad hoc flights were flown on the same day as when the field visits and LAQIs were being flown, so the resources were often used together for assessing habitat and specific indicators. Adhocs were used to overlay the larger site orthomosaics (Google Earth) to focus in on specific areas. The multi-scale UAS images allowed a review from the site level (flight surveys), to a focused habitat area (adhocs/LAQIs), and down to the species level (LAQIs/adhocs) (Figure 91).

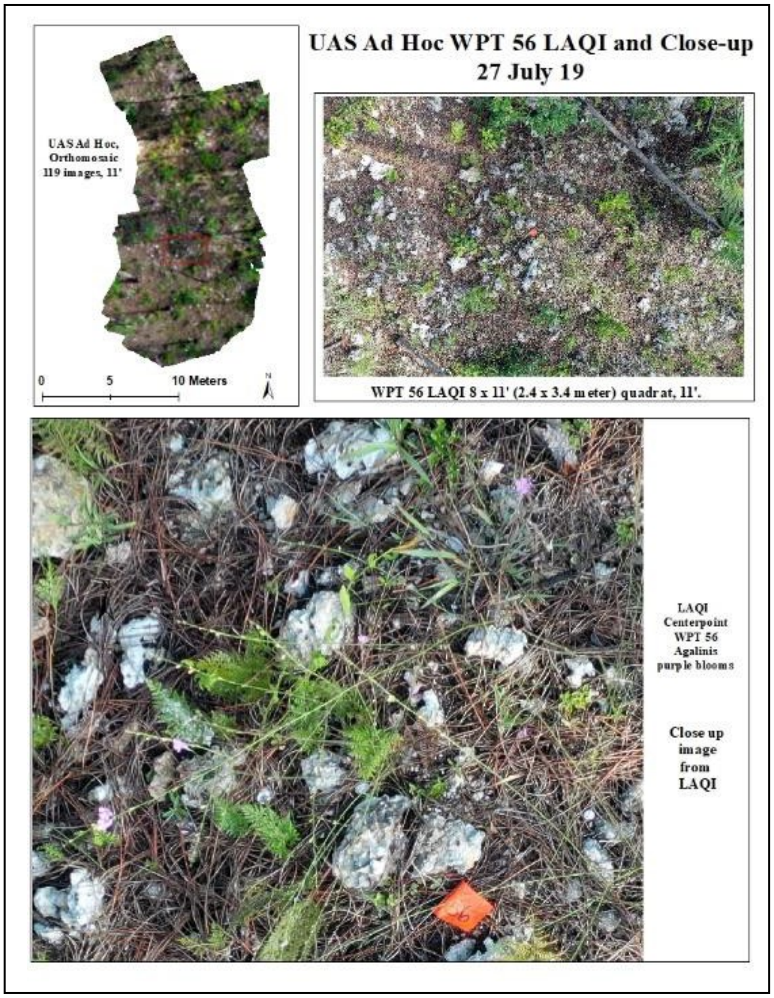
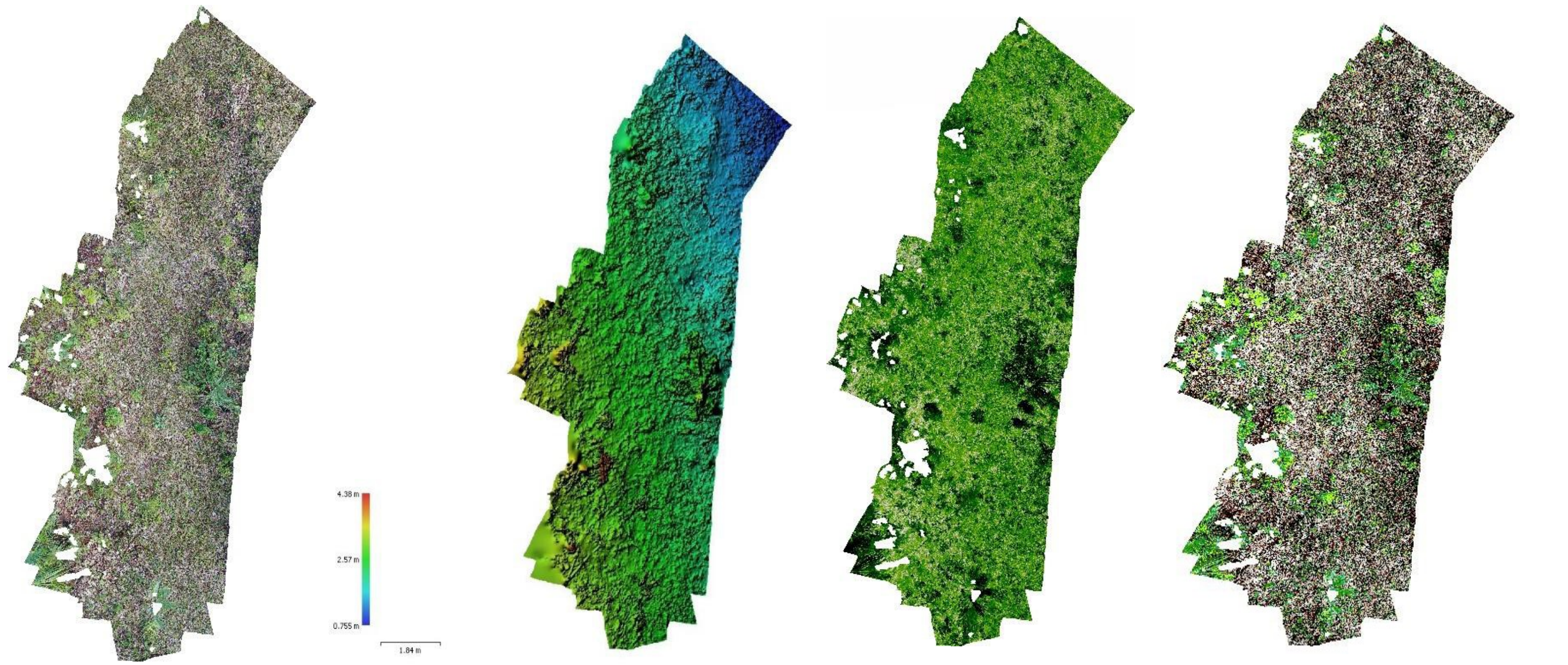


Figure 91. Combined use of ad hoc and LAQI images. WPT 56, *Agalinis*, July 27.2019.

Numerous ad hoc flights were able to be completed with relative efficiency. After completion the LAQI flights and in-field assessments, two to five ad hoc flights were flown that same research day. Logistically, the ad hoc images require less storage and graphic requirements which makes these images easy to process and work with. Although they are limited in size, the products still fill a niche, supplementing the above-canopy flight surveys and the smaller LAQI quadrat images.

Figure 92 provides a catalog of different processed images for adhoc3, December 28, 2019. Each image provided different assessment information. In Figure 92, note the: a) exposed (white) limestone ground cover in orthomosaic; b) shrub texture in the DSM, and yellow pixels of higher shrub, palmetto; c) denser green vegetation in dark green tone and lighter green and white shades of limestone versus dark green shrub; and d) pixel separation of shrub, ground cover, and exposed limestone. A December 28, 2019 cell photo taken within the ad hoc3 flight area provided a ground-level view of the habitat on the day of the flights (Figure 93).



a) Orthomosaic b) DSM c)VARI -0.3 range; NDVI palette d) Unsupervised Classification

Figure 92. December 28, 2019 under-the-canopy adhoc3 orthomosaic, DSM, VARI, and Unsupervised Classification images.

Figure 93. December 28, 2019 Cell Photo of Adhoc3 area; facing north.

Similar cataloging of larger flight surveys can also be developed but the time for processing and sharing capabilities for larger-sized (megabyte) image files need to be taken into account. Smaller cropped, LAQI, or ad hoc representative images can be used for sharing and presentation of information. The ad hoc images presented in these results are the original, unedited orthomosaic images. The saved .tiff, .kml, and .jpg images can be easily cropped and edited (smoothed edges, brightness adjusted) to produce finished image products as needed.

Other UAS image products

Other UAS landscape (Figure 94 and Figure 95) and panoramic (Figure 96) imagery was regularly collected throughout the study. These geo-referenced images were easily acquired at different altitudes and camera angles (not only nadir), either during the TO or landing of the LAQI and ad hoc flying. The August 25, 2019 landscape image (Figure 95) faces to the east into Unit 2B, where a line of burnt, overgrown mid-story shrub remained post-fire and appeared as a line of brown branches across the image, under the canopy. Two, five- to ten-minute, UAS above-canopy videos were also acquired on October 13, 2019, and November 23, 2019, over the Navy Wells Preserve.


Figure 94. Landscape view of ground cover under canopy. Unit 2A. 2.4m (8 ft) altitude. July 6, 2019.


Figure 95. UAS image facing east into Unit 2B, where a line of burned, mid-story overgrown shrub remained post-fire (appears as the line of brown branches under the canopy). August 25, 2019.

Figure 96. PR Panoramic. Navy Wells, Unit 2. UAS image acquired October 5, 2019.

UAS imagery of distinct PR ground cover features

Distinct PR ground cover types were classified and mapped with UAS imagery. Areas of overgrowth of midstory shrub and ground cover, brought on by fire suppression, had distinctively different image classification rasters than those of Unit 2, where the fire had recently occurred. The overgrowth of Unit 4, last known to have burned in August 2014, is characterized by a high incidence of heavy shrub and fine fuels and lack of exposed limestone (Figure 97). Unit 4, as mentioned earlier in the Methods (Section, *Study Site*), is an area documented with high diversity and abundance of rare and endemic PR herbaceous plant species (Figure 3).

The heavy overgrowth of Unit 4 was verified through site visits; the level of shrub overgrowth was to the extent that walking through this “brush” was difficult. Living herbaceous plants were observed under the overgrowth of dead vegetation but were noticeably compromised. The overgrowth was not a loose layer of decaying detritus but consisted of old and dead plant material still on the shrubs and grasses. The old-growth can be compared to what may be seen in a garden where the dead branches, shoots and/or old blooms remain on the plants when not pruned-off. The dead material is slow to decay and stays on the grasses and shrubs, which hinders the robust and healthy growth of those grasses and shrubs. Secondarily, this old vegetation covers the lower herbaceous layer, as illustrated in the LAQIs of Unit 2West (Figure 56) and smothers it. In this situation, the lack of fire prevents the needed “pruning” and thinning of the old vegetation.

Differences in the VARI images are visually evident between areas of heavy grass and low emerging young shrub (hardwood removal and burned within the last yr.)

(Figure 97, left), compared to areas with mature palmetto and shrubs, but with limited green vegetative ground cover (distinctive areas that had not had fire and/or hardwood removal) (Figure 97, right). In Figure 97, ground cover vegetation is shown as green/light yellow color, and shrub and other midstory growth is a red color.

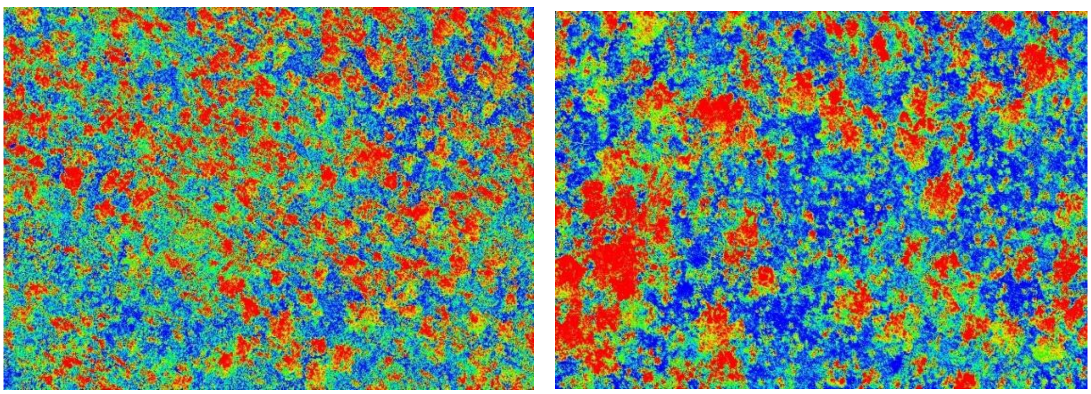


Figure 97. Left: Navy Wells Unit 2, February 19, 2020, grassy area; Right: Unit 4, January 17, 2019, overgrown ground cover. Auto VARI with heat palette.

The overgrowth of the sturdy exotic shrub, Brazilian pine, was documented in Unit 2B-South imagery (Figure 30). Another exotic species, (*Cassytha filiformis*), love vine, was identifiable in the PR UAS imagery by its distinct orange color, and its vegetative growth pattern (Figure 98). Love vine grows parasitically as a tangled vine-form, over and around, vegetation. This pattern appears in the UAS images as a “roundish” ‘cloud’ or ‘blanket’ over the vegetation, depending on density. The invasive vine was often identified by its common occurrence along the habitat edge, where fragments of the vine commonly first take hold (Figure 98).

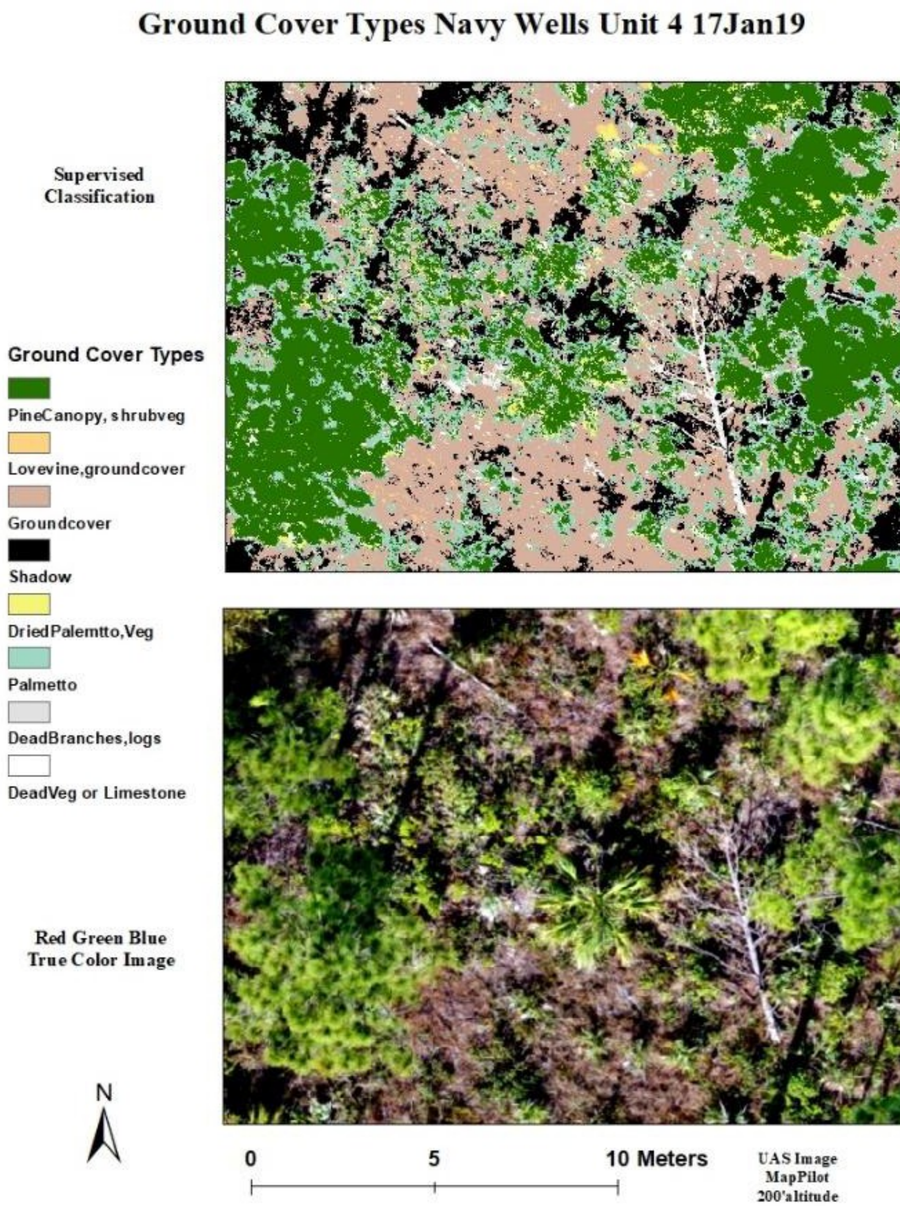


Figure 98. Upper: ground cover supervised classification with sparse limestone; love vine (*Cassytha filiformis*), and Lower: t-c image. Unit 4. Jan 2019.

Pre- and post-prescribed burn (February 3, 2020 burn-date) orthomosaic imagery of the Miami Zoo PR Preserve, Unit 9, is an example of a PR site with dense palmetto shrub (Figure 99). The abundant palmetto was discriminated in the t-c orthomosaic and

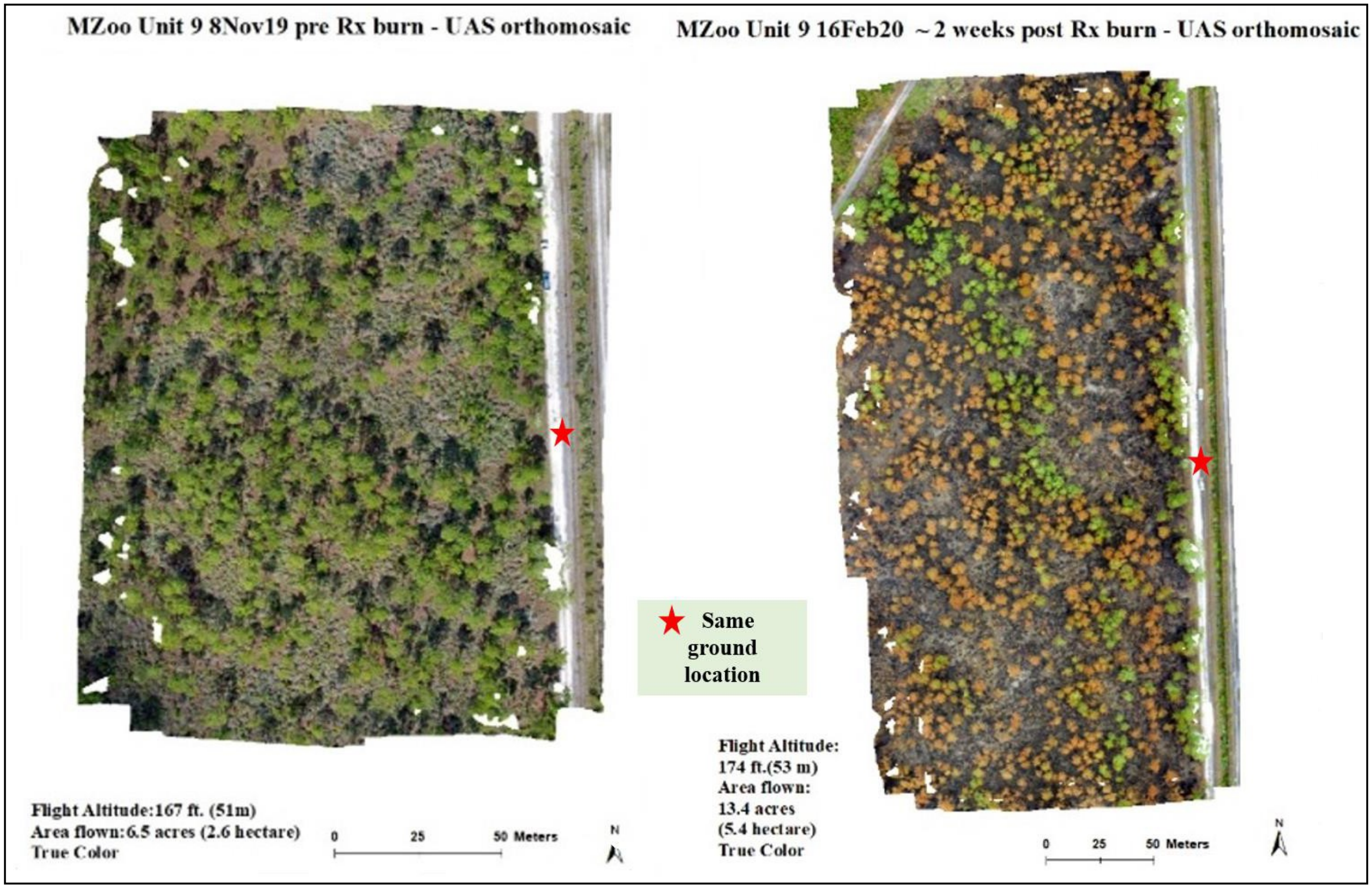


Figure 99. Miami Zoo Unit 9. November 8, 2019 Pre-burn (left); February 16, 2020 post-burn (right). UAS flights. t-c orthomosaic images. February 3, 2020 prescribed burn.

supervised classification by its distinct blue-green (aqua) spectral signature (Figure 99 left, and 100). Small amounts of the exotic love vine were also identified in the scatterplot for the Unit 9 pre-burn supervised classification image, in Band 2, with a light orange signature (Figure 101).

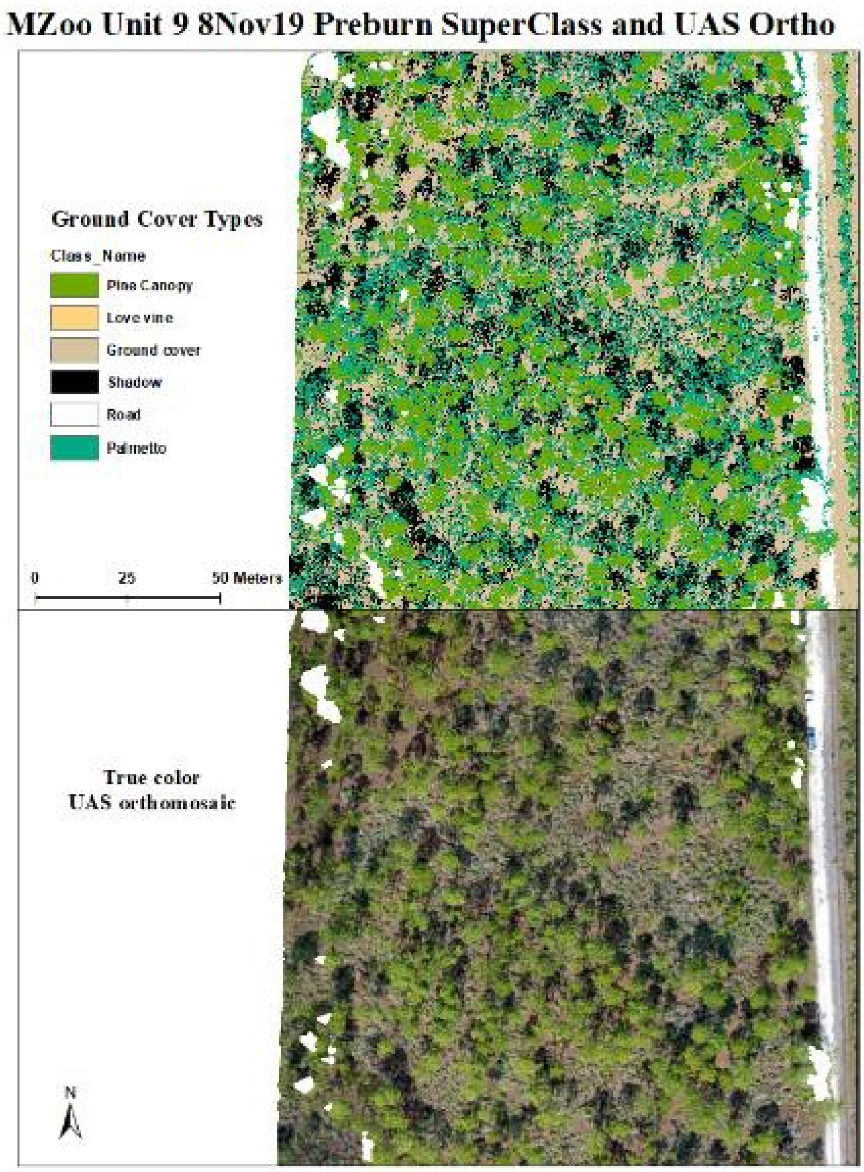


Figure 100. Miami Zoo Unit 9, November 8, 2019 supervised classification: Unit with heavy palmetto. 51 m (167 ft) altitude, 8.8 ha (21.86 ac).

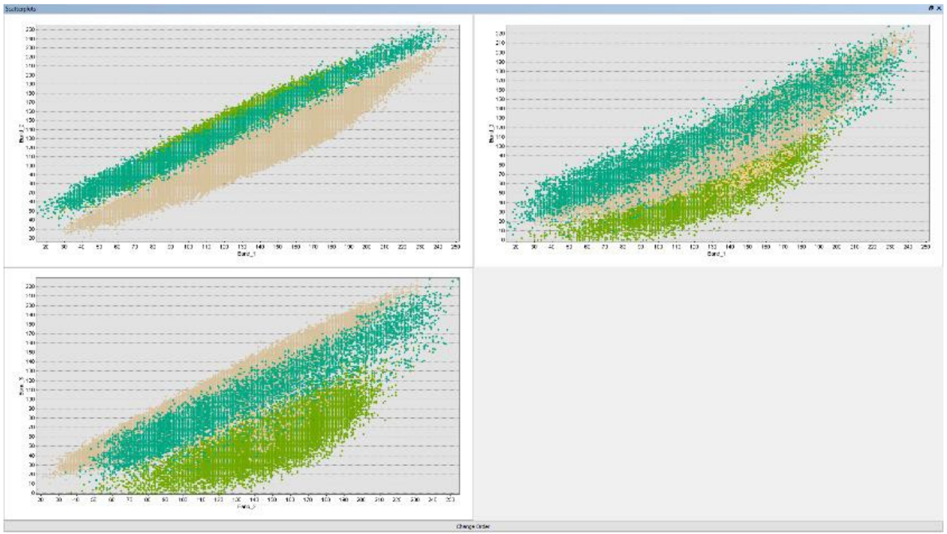


Figure 101. Supervised classification Scatterplot MZoo Unit 9, November 8 2019, Pre-burn land classification pixel separation: Canopy, Palmetto Ground Cover, Love vine.

The unique trunk shapes of the palmetto were also a distinguishing characteristic of the post-burn imagery (Figure 102). The post-burn scatter plot shows the distinct pixel separation between the unburnt (green shade) and burnt canopy (orange shade), and the burnt palmetto (black) and ground cover (gray) signatures (Figure 102). A close-up cell photo of the burnt ground at this site is shown in Figure 103. The degree of separation between the spectral signatures and the predominant classifications of burned palmetto in the imagery provided input on the intensity and extent of the prescribed burn.

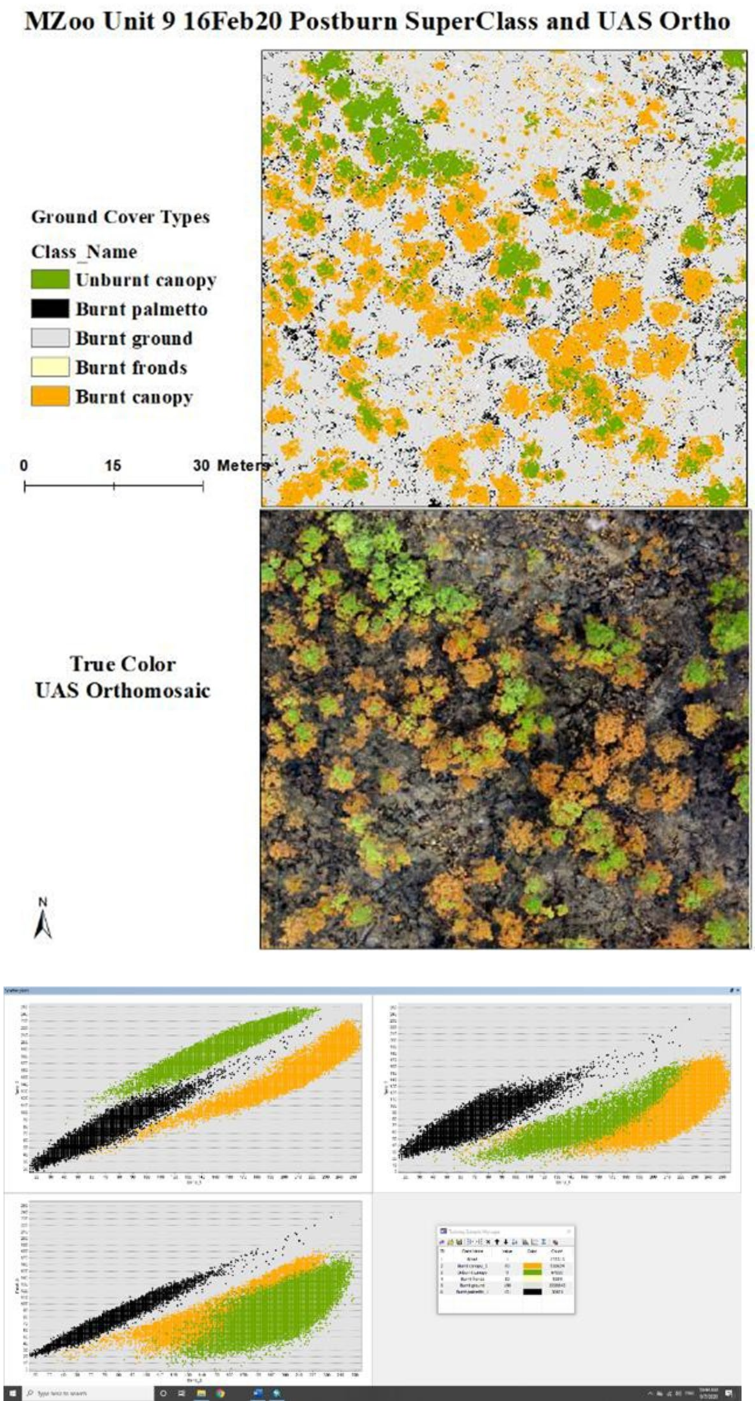


Figure 102. MZoo Unit 9 post-fire supervised classification (upper) and scatterplot (lower) February 16, 2020. February 3, 2020 prescribed burn.


Figure 103. Close-up image of ash and limestone, MZoo Unit 9 post-fire, February 16, 2020. February 3, 2020 prescribed burn.

The November 8, 2019, pre-burn orthomosaic and DSM images of Miami Zoo Unit 10, revealed differences in texture and specific spectral characteristics of features at this site (Figure 104). Miami Zoo PR Preserve Unit 10, consists of a heavy palmetto shrub layer. The fire break that bisects this site is identified in the DSM by its smooth texture and sinewy path across the image, as compared to the “rougher” palmetto shrub layer (blue) and higher pine canopy (yellow/red). The heavy palmetto shrub layer, is evident in the t-c orthomosaic as a light, blue/green shade, compared to the green pine canopy.

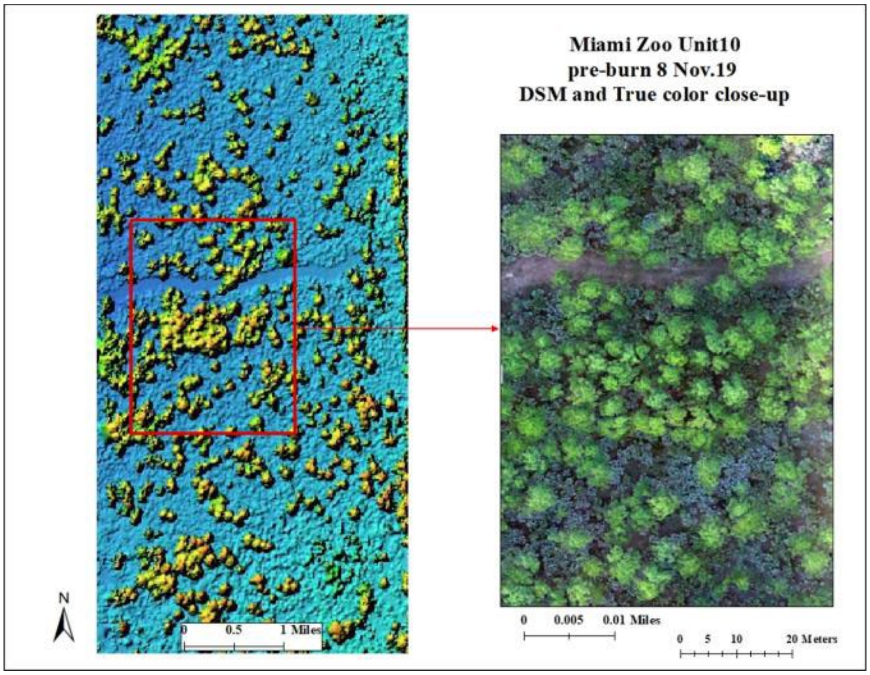


Figure 104. Miami Zoo Unit 10 pre-burn, November 8, 2019. DSM (left), with closeup t-c orthomosaic (right), highlighting fire break, canopy, and palmetto shrub layer.

The fire breaks are used for safety, access, and control of prescribed burns (Figure 104 and 105). Fire breaks through PR can be useful as openings in the habitat for butterflies and beetle movement, particularly in overgrown, unburned sites. However, fire breaks are also destructive, particularly to the ground cover, and further fragment PR habitat. Management decisions in the use of fire breaks and hardwood reductions are made weighing the benefits and detriments of these actions.


Figure 105. Fire break through PR; S. Thompson, M-D land manager.

Density Surface Model

The Navy Wells has a relative elevation of one to two m (three to seven ft) above sea level. It is a flat landscape except for the fine-scale elevation changes and microtopographic variability in the limestone substrate (Figure 106). In Figure 106, a March 25, 2019 DSM of Unit 2A, one of the preserve's flat dirt roads is seen as a smooth, sinewy line (a vehicle is present on the right side of the road), and the Redland soil depression area is evident as the "smooth," round, dark-blue ground layer in the center of the image. This image is seven weeks post-fire, therefore not all vegetation has returned/recovered, and open areas of "smooth" ground cover are visible. The higher shrub vegetation appears as a lighter blue with a "rough" texture. The "rough" area in the top right of the image, with yellow and red shades, is the dense pine canopy that did not burn during the February 2019 fire. The orthomosaic image for this March 25, 2019 survey is shown in Figure 33.

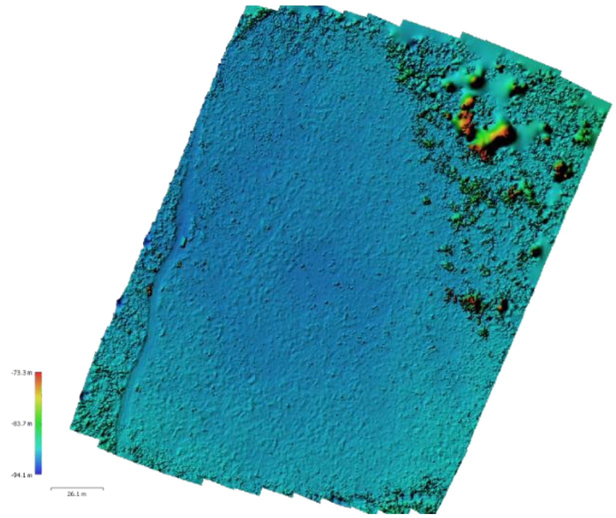


Figure 106. DSM, Unit 2A, March 25, 2019 survey. 46 m (150 ft) altitude.

Figure 107 is an October 27, 2019 DSM of Unit 2A using a heat color palette. The yellow and red shades represent higher shrub and pine.

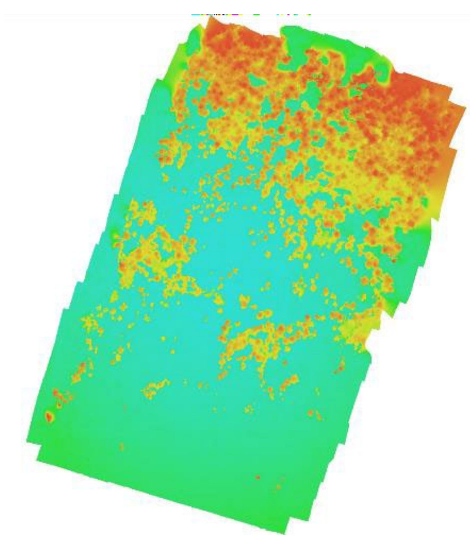


Figure 107. DSM, Unit 2A burn area, October 27, 2019. 51 m (167 ft) altitude.

Relative success was achieved developing DSMs for the small ad hoc images. Figure 108 is a particularly detailed DSM of a November ad hoc image consisting of 77 aligned images. The specific elevation of this area was not verified at the time of the flight therefore, the gradated color pattern is not believed to express the difference in elevation in this small image accurately. The highly detailed texture of the ground layer and downed trees are most notable in this image (Figure 108).

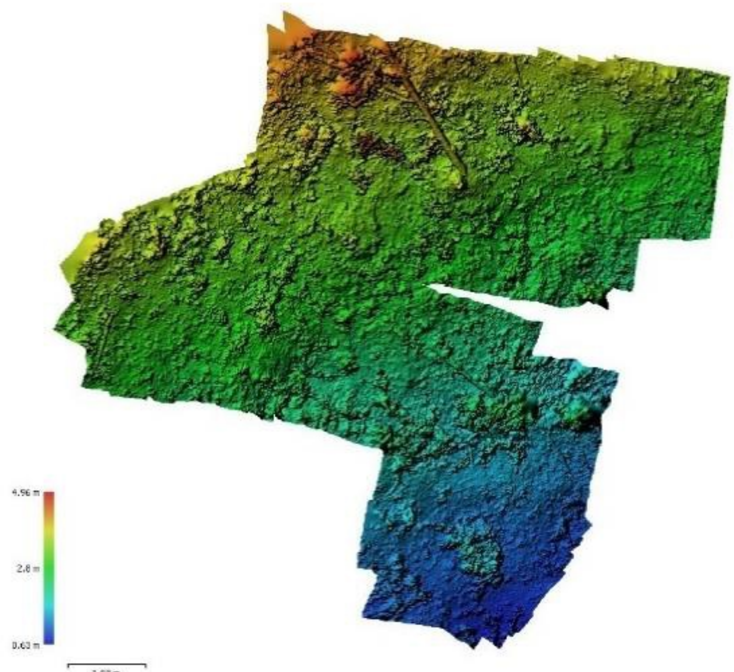


Figure 108. DSM of November 19, 2019 adhoc, 77 images, Unit 2A.

Unit 5-solution hole DSM

Navy Wells, Unit 5 was not affected by the February 2019 fire. Based on M-Dade County records, this unit was last burned with a prescribed fire in January 2010, and at the time of this research, the unit possessed a thick overgrown shrub layer. Unit 5 has a distinct and relatively-large, naturally-occurring limestone solution hole. The circular-solution hole is approximately 1.8 m (6 ft) in diameter, about 1.2 to 1.5 m (4 to 5 ft) deep, and surrounded by a layer of heavy shrubs vegetation. The solution hole can hold water for some lengths of time depending on precipitation, and commonly retains a moist microclimate.

The Unit 5 solution hole is distinguished in DSM and orthomosaic images of the unit as the circular area of heavy vegetation (with a "rough" texture in the DSM), located approximately in the middle of the image (Figure 109 and Figure 110). The DSM image does not indicate the depth of the solution hole, but instead, it can be identified in the image by the circular shape and the spectral signature of the taller and dense vegetation surrounding it. This heavy, surrounding vegetation is supported by the damp, sometimes wet, condition that persists in and around the solution hole. The higher pine tree canopy (red) is also noticeable on the DSM. The flat topography of PR habitat creates a relatively consistent DSM image that shows little variation over time. However, changes in shrub height (some becoming as high as approximately 1.2 to 1.5 m (4 to 5 ft), are visible by the rough texture seen in the DSM image. Additional imagery of the Unit 5 sinkhole is in Figure 111, a) and b).

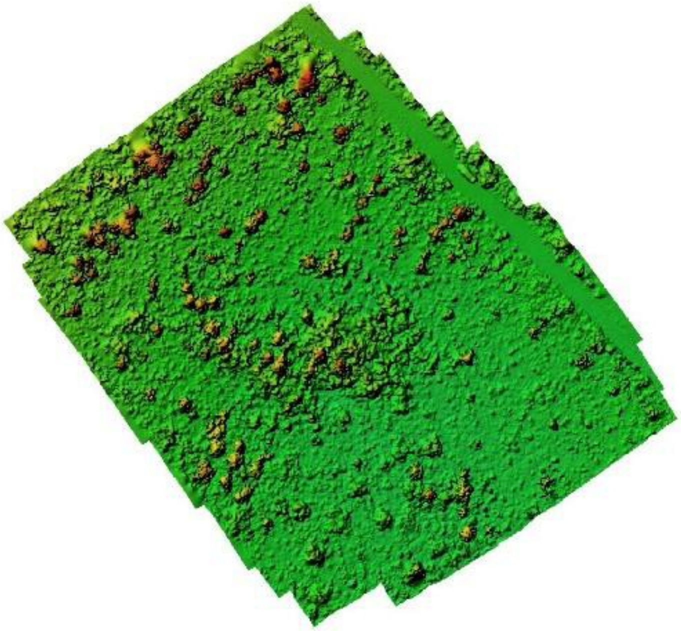


Figure 109. Unit 5 solution hole, March 25, 2019, DSM. Agisoft .tiff captured image. Rough texture of heavy shrub vegetation surrounding solution hole. 46 m (150 ft) altitude; (t-c orthomosaic in Figure 110).

Figure 110. Unit 5 solution hole, March 25, 2019 t-c orthomosaic. 46 m (150 ft) altitude.

The solution hole is also easily distinguished by its unique spectral signature and circular characteristic of surrounding vegetation, as seen in the VARI processed imagery (tree canopy [red]; low shrub [light green]; ground cover [blue]) (Figure 111).

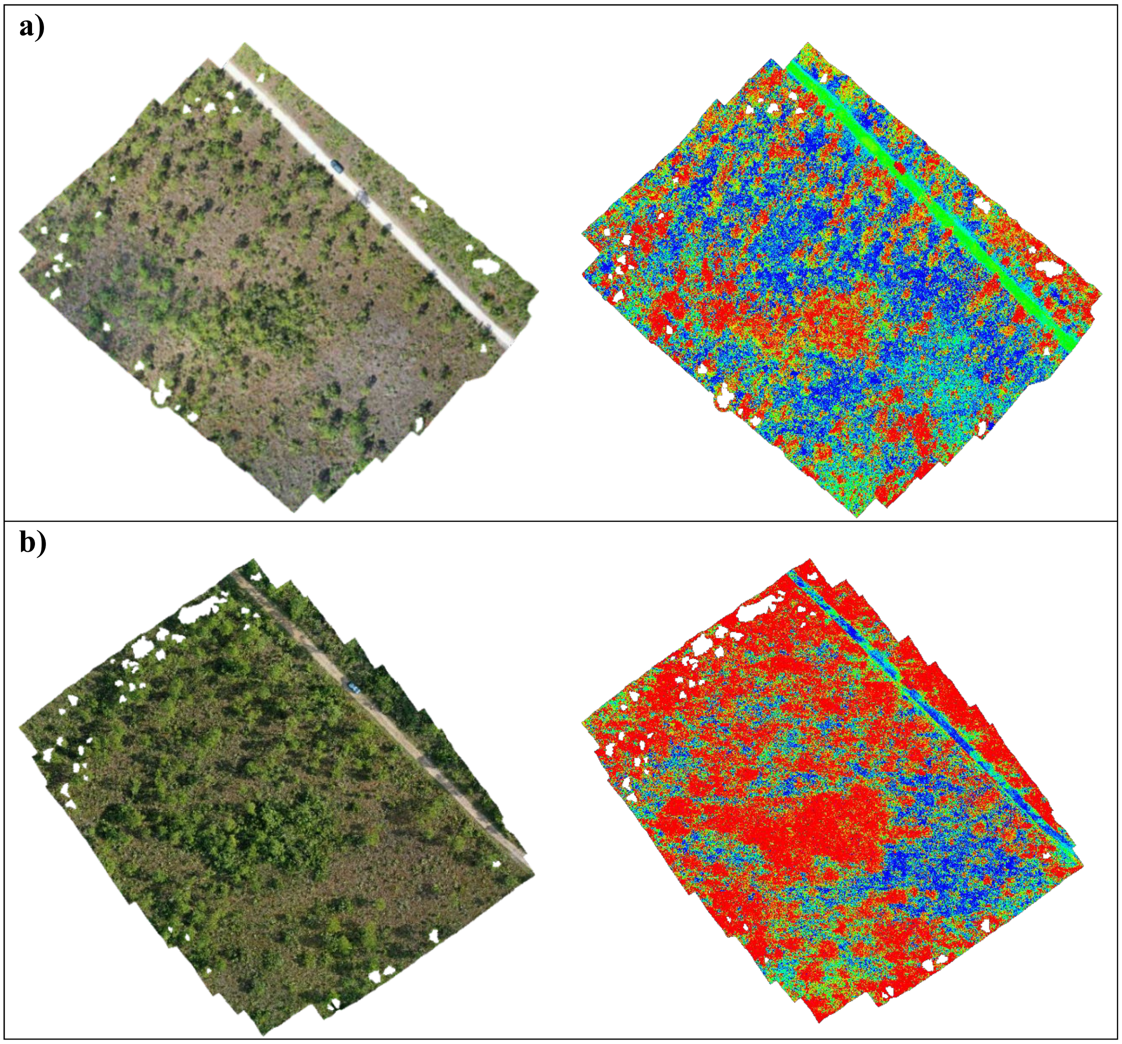


Figure 111. Unit 5 solution hole. t-c orthomosaic, and VARI -0.1 to +0.1; heat palette; a) February 24, 2019 51.8m (170 ft), and b) August 25, 2019, 47.9 m (157 ft).

Close-up UAS images of PR features.

The orthomosaic images produced from the UAS flight surveys (above-canopy) were used to produce close-up images highlighting specific PR features including: a) solution hole Unit 5 (Figure 112); b) depression basin with heavy grass cover Unit2A (Figure 113); c) heavy shrub Unit 2BSouth visible in right (east) third of image (Figure 114); and d) heavy palmetto Miami Zoo, Unit 9 (Figure 115 and 100).

Figure 112. a) Solution hole. UAS aerial survey closeup; Unit 5, March 25, 2019. RGB t-c image, 46 m (150 ft) altitude. Phantom4 Pro+.

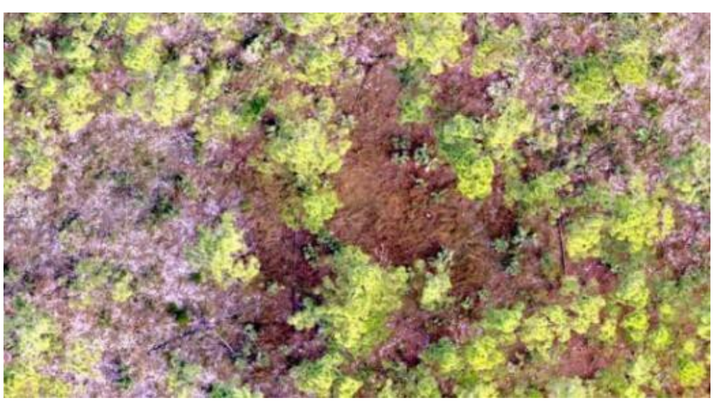


Figure 113. b) Redland soil/grassy depression area, UAS aerial survey cropped closeup, Unit 2A, January 25, 2020, RGB; t-c image, 51 m (167 ft) altitude.


Figure 114. c) Over grown hardwood/shrub. UAS aerial survey; Unit 3 Navy Wells, January 25, 2020, RGB t-c image, 51 m (167 ft) altitude.


Figure 115. d) Heavy palmetto. UAS aerial survey closeup; Miami Zoo Unit 9, November 8, 2019, RGB t-c image, 51 m (167 ft) altitude.

UAS flights with OCN m-s filter and m-s camera.

Two flight surveys, one over Unit 2A and one over Unit 2B, were completed on January 25, 2020, using the Phantom Pro+4 equipped with the Survey 3 camera and the MAPIR OCN m-s filter. A single flight with the OCN m-s filter consisted of 316 images.

Images were aligned and processed into an orthomosaic image using the Agisoft workflow for m-s cameras (Figure 116).

The OCN filter was experimentally-used in this research to examine its potential to separate PR canopy vegetation from ground substrate (refer to *Methods* Section). The OCN filter is primarily advertised for agriculture to separate a crop from the ground soil. The purpose of this OCN filter is to highlight and separate ground cover using the O-C- and N-bands. In these OCN images, the low-level ground cover, vegetation and limestone, would be spectrally separated from the pine canopy of the PR habitat.

The resulting image of flights over Unit 2 was not found to discriminate, or separate PR ground cover vegetation types from pine canopy as well as the three-band, RGB imagery acquired with the UAS cameras. However, the habitat under-the-canopy, as a whole, was found to be distinct from the pine canopy in the resulting raster (Figure 116 and Figure 117). The ground layer was green/aqua in the OCN image, and the pine canopy vegetation presented as a pink shade. While the OCN filter distinctly separated the canopy from the ground (or the ground from the canopy), the RGB images of this same site provided for a better separation of the various spectral classes and for discriminating the various class types of the PR ground cover (Figure 116 right side; Figure 117, closeup).

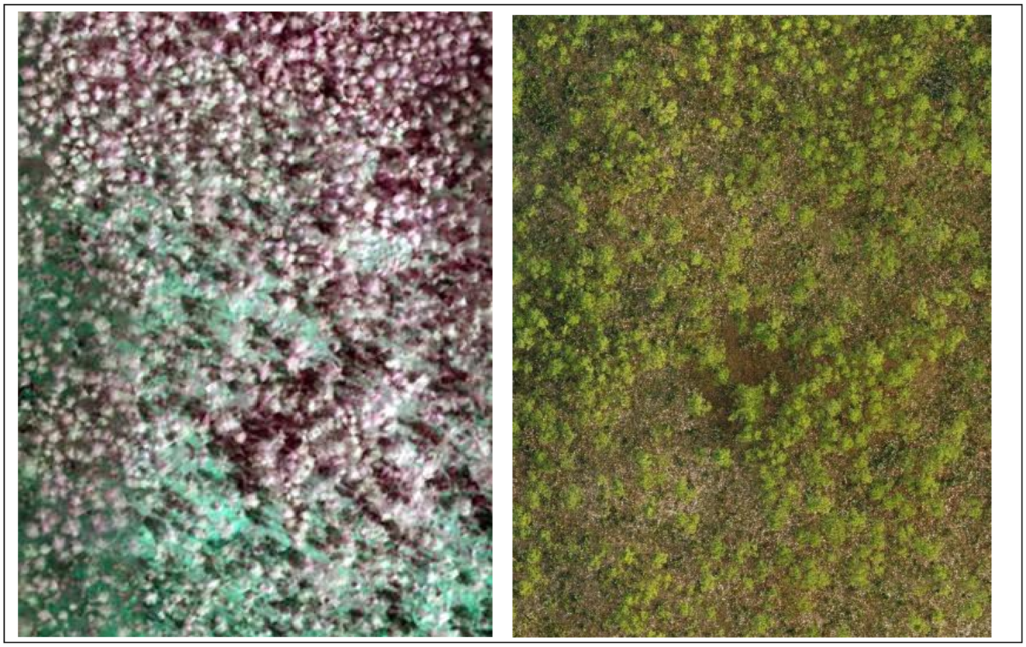


Figure 116. Orthomosaic images: Left: OCN m-s filter. Right: t-c. Navy Wells Unit 2A cropped images, January 25, 2020. In OCN image, pine canopy and green vegetation are shades of pink; ground cover present as shades of green/aqua.

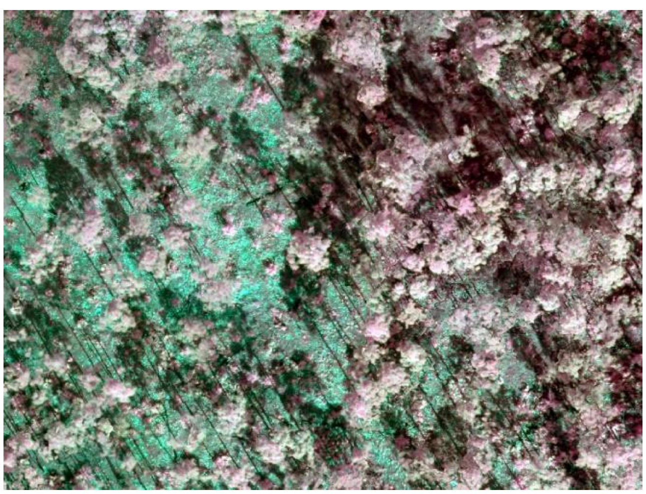


Figure 117. Close-up of OCN orthomosaic image from Figure 116. Limestone and ground cover is represented by green/aqua. Green vegetation (pine canopy, shrub, and grasses) indicated by shades of pink.

An unsupervised classification raster was processed with the Unit 2A OCN orthomosaic t-c image (Figure 118). The pine canopy class was separated from the low-level ground cover but fewer variations in ground cover types were identified compared to the results of the RGB image classifications.

The OCN m-s filter is meant to provide a greater discrimination of ground cover from green vegetation using the NDVI index, than with a RGN m-s camera. A comparison between a RGN m-s and an OCN orthomosaic image processed using the NDVI index, is shown in Figure 119.

Only two OCN flights were able to be flown, so the ability to conclude is limited. The 2020 Covid-19 pandemic prevented further site visits, and additional flights with the OCN filter were impossible. Further study is needed, but the OCN filter showed potential as an assessment tool for visually separating spectral signatures of the PR substrate and lower ground level vegetation with the pine canopy.

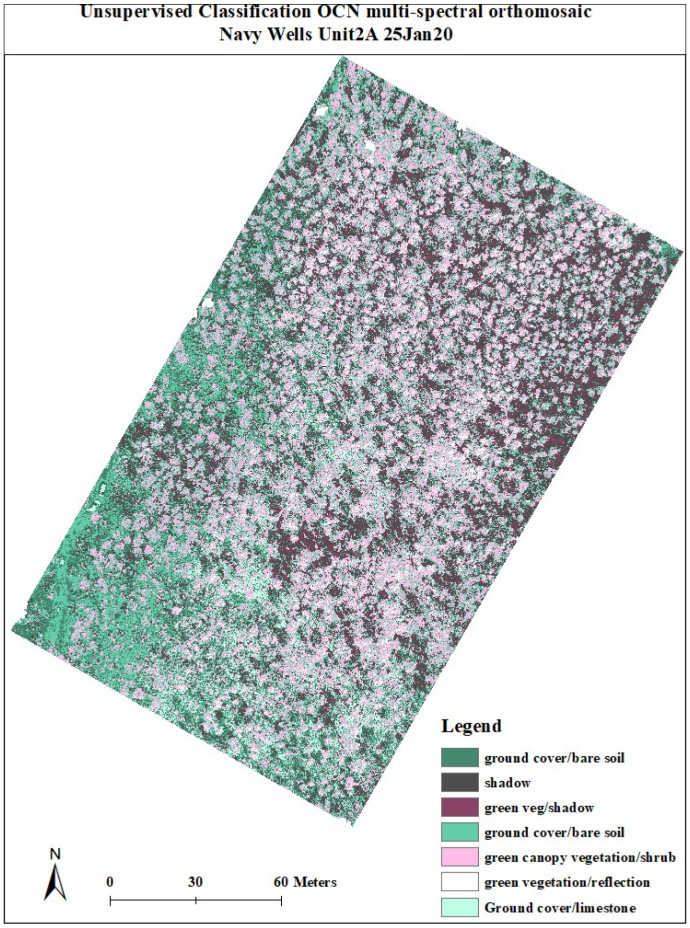


Figure 118. Unsupervised classification of OCN m-s orthomosaic. Navy Wells Unit 2A, January 25, 2019, 52 m (171 ft.) altitude.

NDVI with OCN and m-s images

RGB imagery was predominantly used for this research. However, two UAS flights were flown in Unit 2A in June 2019, using a RedEdge m-s, RGN, camera in cooperation with USFWS UAS pilots (flown prior to the DOI UAS program being grounded by the Administration). These images and values from the NDVI calculations were used with the OCN NDVI processed images, to contrast "healthy" green vegetation with "not healthy", or "not as healthy" (green vegetation) (Figure 119).

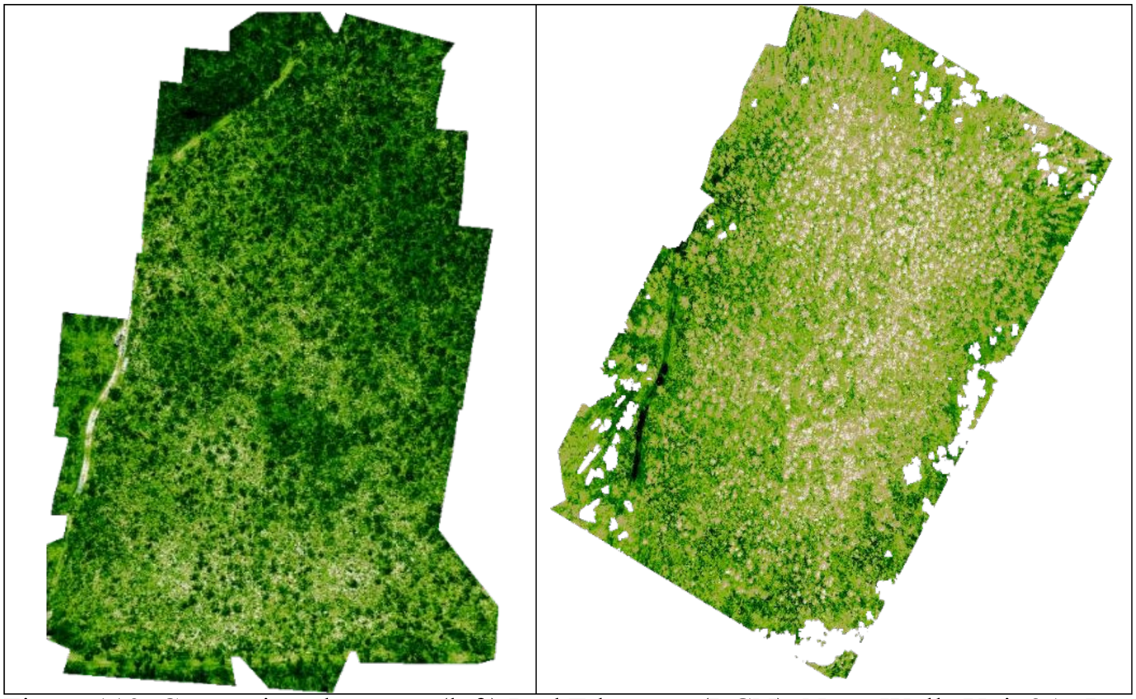


Figure 119. Comparison between (left) Red Edge m-s (RGN), Navy Wells Unit 2A, June 9, 2019 NDVI, 56 m (183 ft) altitude); and (right) OCN filter Navy Wells Unit 2A January 2020 using NDVI; 51 m (167 ft.). cropped images. Note the road on left side of each image for reference.

The NDVI index calculated for the RedEdge m-s, June 9, 2019, image resulted in range of +0.89 to -0.19. The January 25, 2020, m-s OCN image resulted in an NDVI value of +0.54 to -0.18. Either m-s images can be used to calculate an NDVI index for classifying PR habitat types. However, the RedEdge and the OCN NDVI results cannot be compared against one another since the m-s RedEdge is developed from a single RGN sensor, and the m-s OCN is a filter used on a camera. The NDVI values that result from the OCN filter can only be compared to other images using the OCN filter.

With a local understanding of the area and the different habitat types, and knowing in an image what represents "healthy" vegetation and what is "not healthy" vegetation, it is possible to build an inventory of Index values as a key for the PR site (preserve). As an example, in the PR habitat in the OCN NDVI index, the lower values (into the negative values) correspond to the ground pine needles and limestone substrate (light/white colors), with the higher positive values representing the pine canopy. More flights are needed to establish the given range for the midstory-shrub and other shades of green vegetation of the PR system.

Supplemental Imagery Results

The online USGS EarthExplorer image resource site (available to the public at no cost) was used for researching and downloading satellite and historical aerial photos. The M-D County aerial imagery from 1999-2019 (M-D County 2020), Florida FWC burn data satellite (FWC 2021), and Navy Wells rare plant survey data (FTBG 2017) were used as supplemental imagery data in assessing the PR system.

Navy Wells Pineland Preserve Prescribed Fire History

The fire history for the Navy Wells study site was obtained by the M-D Natural Areas Management (NAM) Park and Recreation Department GIS Unit, with additional information obtained from the Florida FWC Fire Occurrence GIS Viewer (Table 7; Figure 120) (Miami-Dade County 2019; FWC 2021). Figure 120 presents a screen capture image of the FWC's prescribed fire history for the Navy Wells PR from 1994-2021. The M-D County maps provided shapefile graphics of the fire footprint, type of fire, and size (in ac) for each fire documented by the County on the site from 2006 to 2010 (M-D County 2019). The FL FWC fire occurrence 1994-2021 data provided additional information on the burn history for the site (Table 7). The FWC Fire

Occurrence data was delineated from Landsat and USGS Burned Area (BAECV ver.2) algorithms that Tall Timbers Research Station developed for FL FWC.

Table 7. Navy Wells FWC Fire Occurrence data 1994-2021

Florida Fish and Wildlife Commission Fire Occurrence Data Navy Wells Units 1-6, and 8 2006-2019*							
	Unit 1	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**	**Unit 6****	**Unit 8****
Burn Yr.	2016	2019 - reported by M-D County as arson	No fire information in FWC database for this unit	2014	No fire information in FWC database for this unit	2006 - reported by M-D County as wildfire	2010
Yr. last burned	2016	2019		2014		1994	2010
Time since previous fire	4 yrs.			6 yrs.		12 yrs.	9
Largest fire free interval	22 yrs.	25 yrs.		8 yrs. (Aug. and Nov. 2007 Rx)		26 yrs.	9
Acres	7.94			22.46		6.02	12.06

*FWC 2021 (FL FWC GIS and Mapping Database Online Map Viewer.
**Units 6 and 8 were not part of research study site.

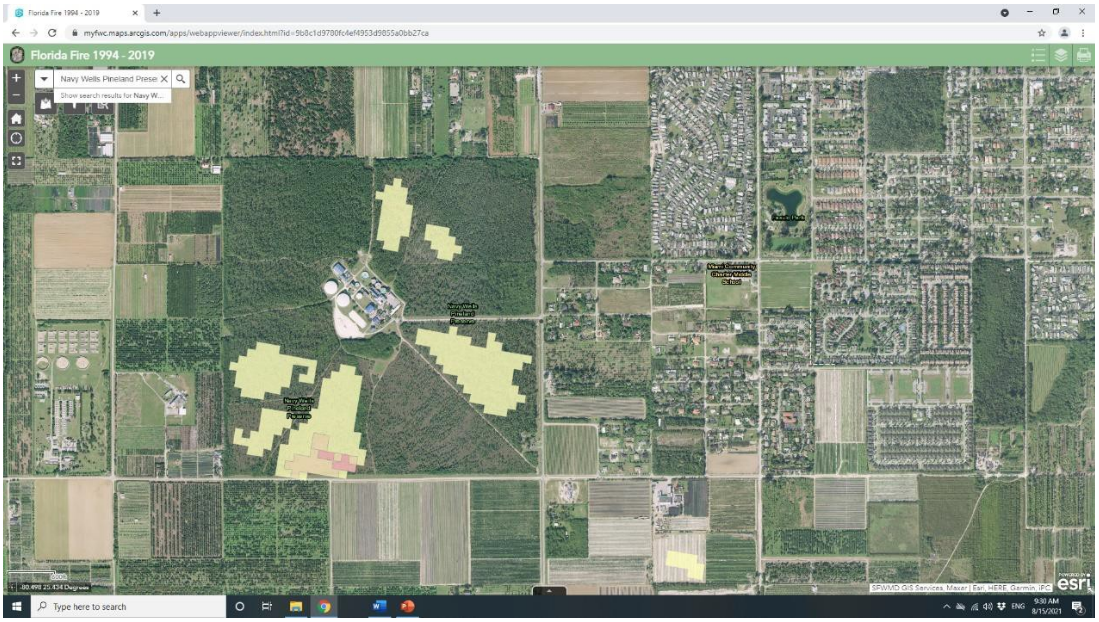


Figure 120. Screen shot of FWC Fire Occurrence GIS Viewer illustrating fire history (light green areas) for Navy Wells study site.

A summary of the combined M-D County (2019) and FL FWC (2021) fire history data for Navy Wells Units 1 through 5 are presented in Table 8. The field-work and UAS flights for this research took place in Units 1-5. Baseline UAS flights were flown in Navy Wells, Units 6-8 in January 2019, however, these areas were not included in the research study site. Units 1-5 were used in this study because of a recent fire, prescribed fire management and hardwood removal activity, unique feature (limestone solution hole), and the documented high presence of rare plant diversity within one or more of these units.

Table 8. Navy Wells Unit 1-5 Fire History (Miami-Dade County and FWC data)

Summary of Navy Wells Unit 1-5 Fire History* Fire Yr., Type, Acres (ac)				
Unit 1	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**
2016, Rx**, 7.94 ac (data also reported in FWC database)	February 2, 2019, arson wildfire, 29.9 ac.	Jan. 26, 2010, Rx, 15.9 ac.	2014, Rx, 22.46 ac.	Jan. 24, 2010, wildfire, 9.6 ac.
	November 29, 2001, Rx, 11.9 ac.		August 17, 2007, Rx, 9.4 ac, west side.	Jan. 24, 2010; Rx counter fire, 33.8 ac.
			November 27, 2007, Rx,26 ac, east side.	Nov. 4, 2004, 39 ac.
			November 1987, Rx, 84 ac with Unit 5.	November 1987, Rx, 84 ac with Unit 4.

*FWC 2021; M-D County NAM (Miami Dade County 2019).
**Rx = Prescribed fire.

Landsat satellite view and fire footprint

USGS EarthExplorer Landsat and Landsat Legacy satellite collections of S FL between 2017 and 2020 and that incorporated the Navy Wells site were reviewed. Image filtering was based on identifying “low-cloud” images and selecting images from both the wet and dry season. Images were selected from Landsat satellite 8 OLI, and Landsat 7 ETM imagery files, and reviewed to confirm the Navy Wells site was visible in the image. The following Landsat 8 OLI images were used in the results: LC08_L1TP_015042_20180926_20181009_01_T1_MTL (approximately four months pre-wildfire), and LC08_L1TP_015042_20190217_20190222_01_T1_MTL (12 days post-wildfire fire).

A m-s, NDVI satellite image of S FL (Miami, ENP, and Homestead), with the boundary of Navy Wells study site highlighted, is shown in Figure 121. This image provides a regional perspective and emphasizes the small, highly-fragmented preserves of the S FL PR system (Appendix 2). The Landsat imagery is a gross (30 m) scale compared to the lower spectral resolution compared to the (10 cm) vHR available with the UAS sensors.

High, positive NDVI values characterize subtropical S FL due to heavy green vegetation, but agricultural fields and the high moisture levels from heavy rainfall are represented by lower NDVI scores and appear in this image in shades of red and yellow. The NDVI index range for this image was +0.63 to -0.30.

NDVI values calculated for the September 26, 2019 and February 17, 2019 Landsat images ranged from +0.63 to -0.30 to +0.58 to -0.23, respectively (Figure 121 and Figure 122). Calculated NDVI values of Landsat images varied depending on season and amount of green vegetation and moisture (high positive values for green vegetation), with some of the Landsat images, not included as figures in this dissertation, resulting in an NDVI range of +1.0 to -1.0.

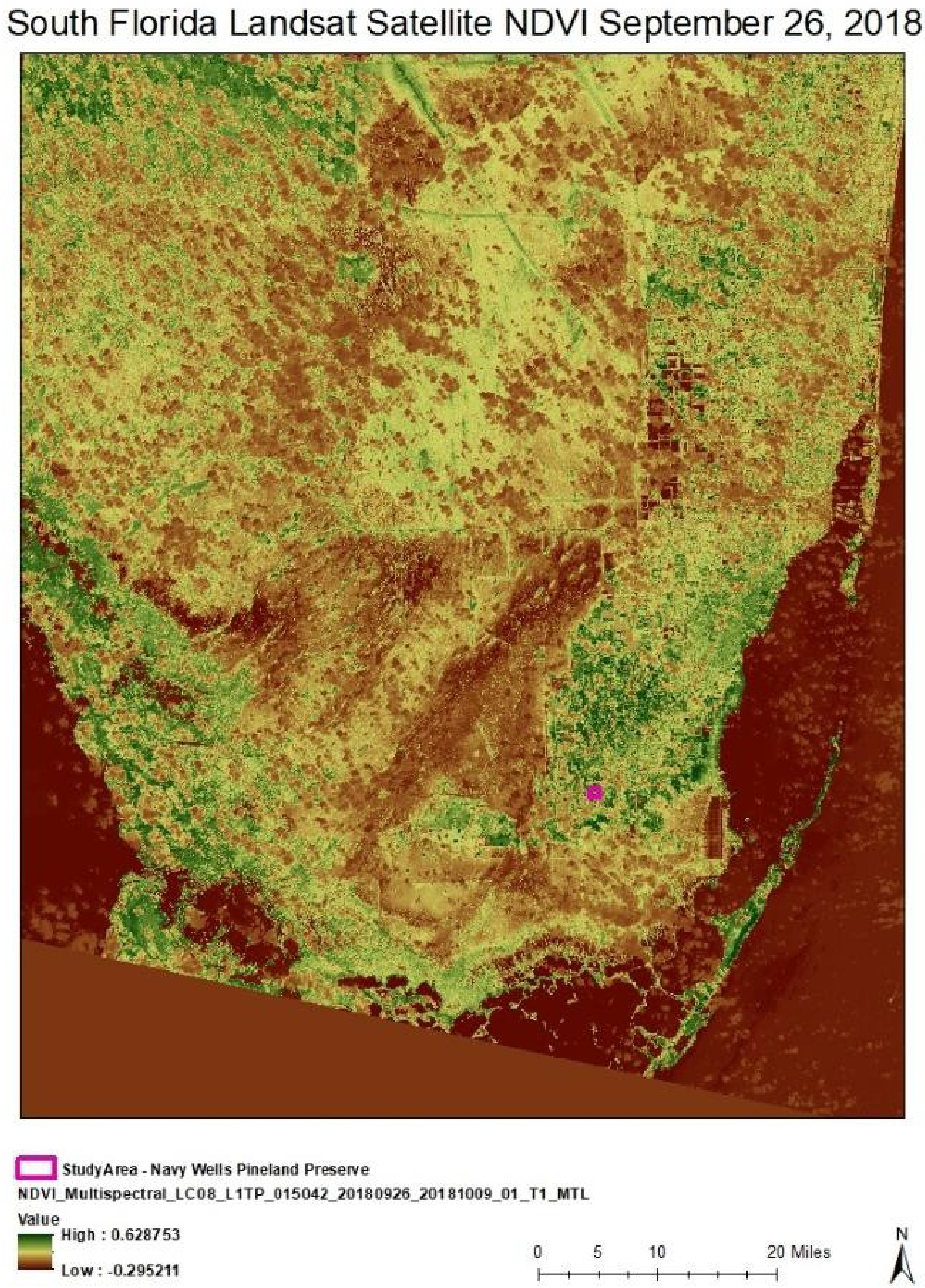


Figure 121. NDVI image of S FL, Everglades, and Homestead with the study site highlighted.

Clipped images of Navy Wells from the September 26, 2018, and February 17, 2019 satellite images are shown in Figure 122. The NDVI *pixel values* found across the

Navy Wells units generally ranged in values between +0.3 to +0.4. The dense area of the invasive Brazilian Pepper present in the Navy Wells site (Unit 3, east side) was visible in the Landsat imagery as a very dark green shade, and had an NDVI (*pixel value*) of +0.5.

Landsat images for viewing small parcels were often hindered by cloud cover and shade in this tropical environment. These images were too large in scale for detailed examination of the small, fragmented PR systems, particularly of the ground cover. While they provide a regional and local perspective for surrounding land classification and habitat fragmentation, these images were not sensitive enough and were not used for identifying specific PR habitat indicators. One of the best uses of this imagery was to document the pre-fire; immediate post-fire; and the subsequent images one-yr. post-fire and beyond, of the restored system. The (white) hotspot of the February 6, 2019 fire is evident in the February 16, 2019 Landsat image (Figure 122; lower image). Advantages of the satellite imagery are the dependable, repeated overflights, and the high volume of freely available imagery.

UAS orthomosaic images were overlayed with Landsat satellite images in ArcGIS, or in Google Earth to provide an overview and catalog of the completed UAS flights. Figure 123 shows an example with just two of the UAS images flown over Unit 2 overlayed on a close-up satellite image of the site.

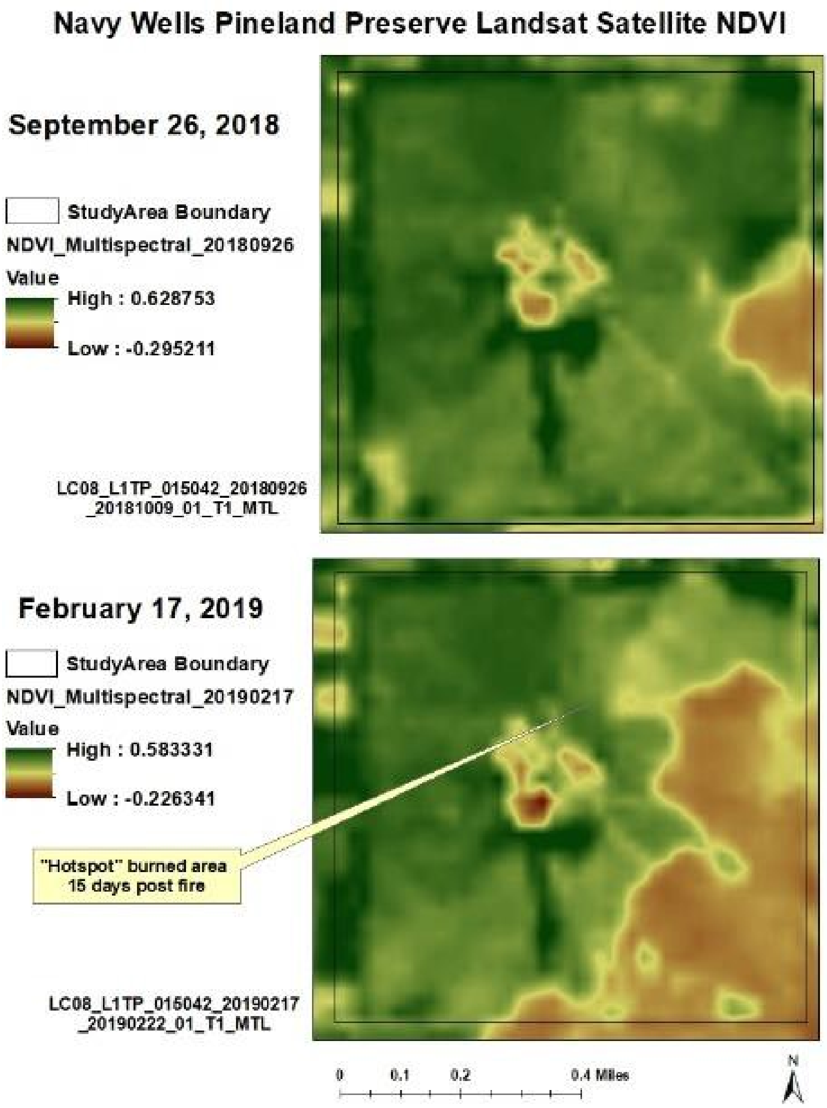


Figure 122. Clipped NDVI images of study site from Landsat satellite. The white hotspot of the February 2, 2019 fire in Unit 2 can be identified in the lower image.

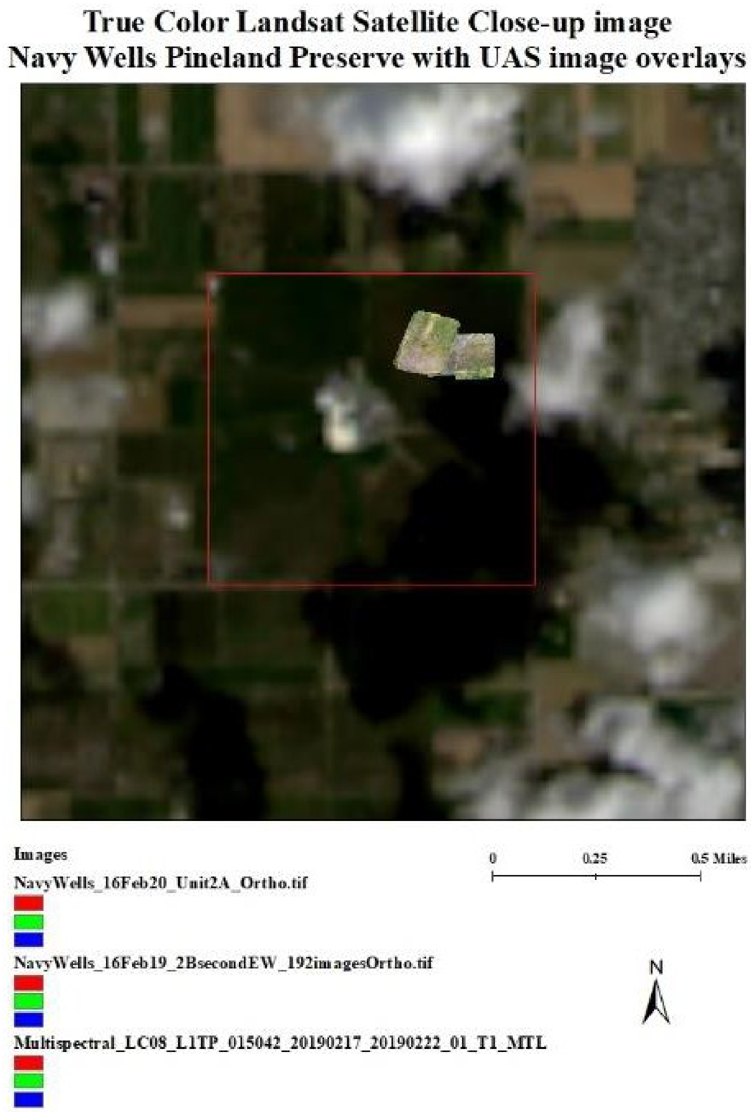


Figure 123. February 16, 2019 Landsat satellite closeup of the site, overlayed with orthomosaic images of two UAS flights flown over Unit 2.

Historical black-white aerial imagery.

Historical, archived, single, black and white images from 1950 to 1979 obtained from USGS EarthExplorer were reviewed. These aerial photos document human development, changes in land classification, and the urban interface surrounding the PR study site over time (Figure 124 to 130).

Figure 124. Navy Wells, November 1950 black and white aerial image. USGS. Red arrow points to Navy Wells. 7009 m (29,995 ft) flight altitude.

In Figure 124, Navy Wells is located on the left-middle side of the image; surrounding, open space to the southeast of Navy Wells is still present in this image. Signs of freshwater flow can be noted by the light striations approximately north to south. In a 1952 image (Figure 125), agriculture (rectangle shapes) is visible to the north and south of Navy Wells. However, a large amount of existing, intact PR habitat can still be seen as existing around Navy Wells.

Navy Wells is seen intact in 1964 (Figure 126). A rectangular intact section of PR habitat to the NE corner of Navy Wells (dark shade) visible in this 1964 image had been slated for housing development. The 1969 NIR image (Figure 127) shows the same rectangle parcel of what was PR habitat in Figure 126, now totally cleared (bright white).

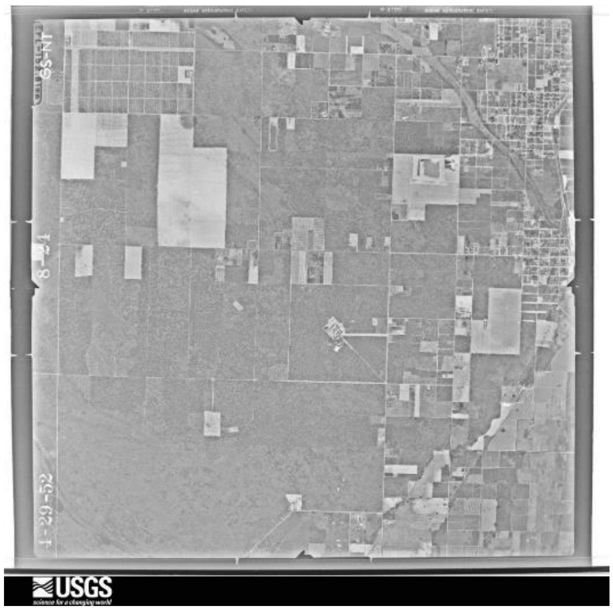


Figure 125. Navy Wells 1952, 4328 m (14,200 ft) flight altitude.

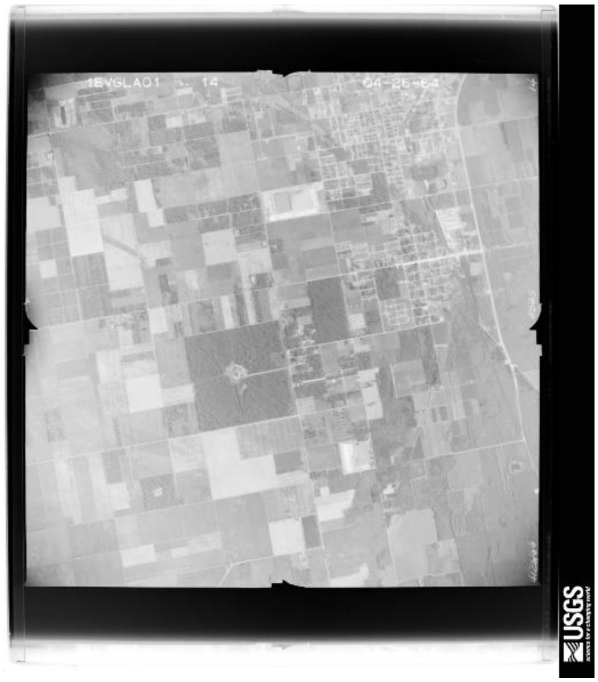


Figure 126. Navy Wells and a small PR parcel to the northeast of Navy Wells, April 1964, 4420 m (14,500 ft) flight altitude.

slated for housing development. The 1969 NIR image (Figure 127) shows the same rectangle parcel of what was PR habitat in Figure 126, now totally cleared (bright white). In Figure 127, the eastern half of Navy Wells is visible in the middle-left of the image.

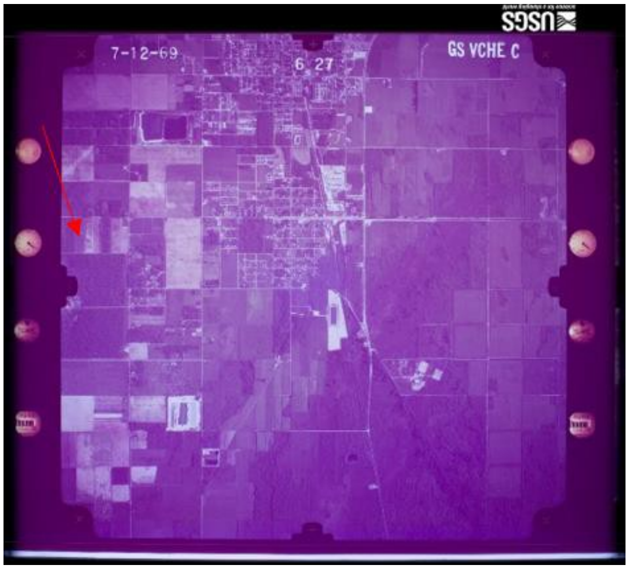


Figure 127. Partial image of Navy Wells. 1969 NIR. New housing development to the northeast of Navy Wells (white rectangle; cleared land) where PR existed in April 1964 (Figure 126). 3658 m (12,000 ft) flight altitude. Red arrow points to Navy Wells.

Navy Wells is surrounded by urban landscape and agriculture by 1970 (Figure 128). In Figure 129, 1979, Long Pine Key and the water pattern of the transverse glades are visible in the bottom left of the image. A closeup of image Figure 129, Navy Wells, (Figure 130) clearly identifies the housing development (visible street pattern; houses) now in place to the northeast of Navy Wells, compared to Figure 126, where the PR habitat once existed.

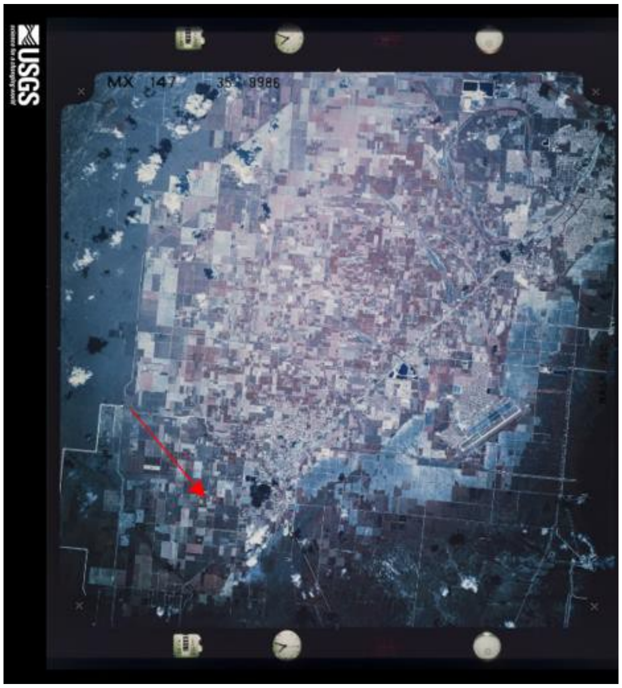


Figure 128. Navy Wells, 1970 NIR. Red arrow points to Navy Wells, 18,240 m (59,842 ft) flight altitude. Urbanized and agricultural surroundings.

Figure 129. Navy Wells 1979. Red arrow points to Navy Wells, 1219 m (4,000 ft) flight altitude.

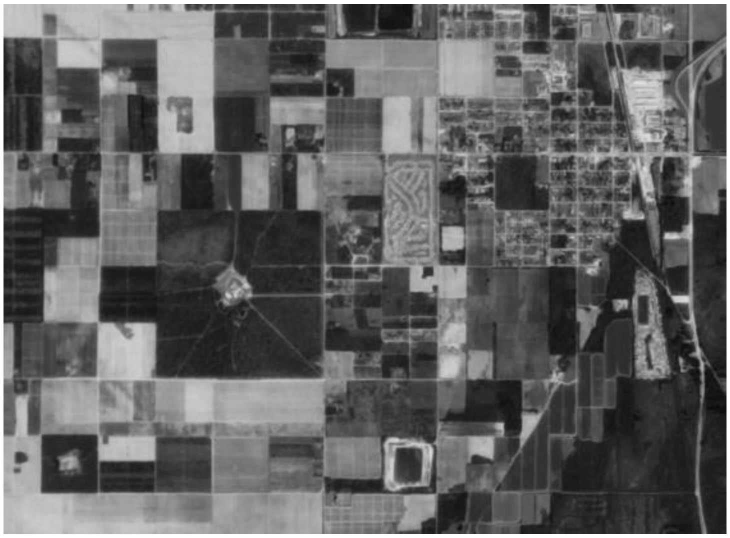


Figure 130. Navy Wells 1979; Close up and clipped from Figure 129 aerial image.

Current County aerial surveys

Annual aerial survey color images were downloaded from the M-D County GIS portal and used as a time-series review of noteable events and overall condition of the site. Between two to 16 grid raster images were mosaicked with ArcMap 10.8, per single aerial image of the study site, for 2006, 2007, 2015, and 2019 (Figure 131 to 133). The 2006 imagery shows signs of vegetation decrease due to impact from catastrophic Category 5, Hurricane Wilma in October 2005 and existing drought conditions of 2006 (Figure 131).

Figure 131. Upper: Navy Wells aerial survey early 2006 and Lower: 2007. 2926 m (9600 ft) flight altitude. Grid images downloaded from M-Dade County GIS portal.

The 2015 image (Figure 132) illustrates the 8.9 ha (22-ac), 2014, prescribed burn in Navy Wells Unit 4 (Unit 4 identified in Figure 3). A 2019, aerial image of the study site, before the February 2019 fire, is shown in Figure 133. This aerial can be compared to the same image used in the Figure 3, with the February 2019 burn footprint (Methods, *Study site*).

Figure 132. Navy Wells 2015 aerial image; after a 2014 prescribed burn in Unit 4.

Figure 133. Recent 2019 aerial image of Navy Wells; captured just prior to February 2, 2019 wildfire. (Also Figure 3).

Unit 4 rare plants

Rare plant surveys completed by PR expert botanist J. Possley at Fairchild Tropical Botanic Garden are overlain with UAS flight surveys (FTBG 2017; Figure 134). Close-up examination of individual plants and feature data points were possible using the high spatial definition UAS imagery. UAS Flights were flown in selected units of the study site to capture imagery of a) specific areas with a high-density of rare plants (Unit 4), and b) a single, rare and endangered Everglades bully (*S. reclinatum spp. austrofloridense*) plant that had been identified in field surveys (Unit 5). At the time of this study, foot travel through the Unit 5 site was particularly difficult due to heavy shrub overgrowth and poisonwood. A small scale UAS image could be used to document the location where this single species had been previously recorded (Figure 134).

Figure 134. 2014/2015 rare and federally listed plant survey (shapefiles) overlain onto UAS flight surveys. Rare plants survey: (FTBG 2017). Yellow thumbtack marks the location of rare, endangered, Everglades bully plant.

Cell Photos

Geo-referenced cell photos were used as supplemental information of PR species and habitat characteristics (including those selected as PR indicators). A collage of selected cell photos taken during the research is in Appendix 8. Two PR endemic plant species include the Florida noseburn, *Tragia saxicola* (Figure 135) and the pineland poinsettia (or pineland spurge), *Euphorbia pinetorum*, (IRC2021) (Figure 136).

Figure 135. The endemic Florida noseburn, *Tragia Saxicola*. Abundant in Navy Wells Unit 2. June 16, 2019 cell photo.

Figure 136. The dainty endemic Pineland Poinsettia, *Euphorbia pinetorum*. September 7, 2019 cell photo.

The endemic Pineland deltoid spurge (Pineland sandmat; *C. deltoidea ssp. pinetorum.*) is a common subspecies occurring in the study site, and other PR preserves (Figure 137; Figure 79; Figure and 48). The deltoid spurge appears as low-profile clusters and plays a significant role in being one of the first PR ground cover plants to emerge post-fire. It may be uniquely, ant-pollinated (Austin 2015).

Figure 137. Pineland deltoid spurge, *C. deltoidea* ssp. *pinetorum*. June 21, 2019 cell photo. Low-profile emerging from nooks and crannies of the limestone substrate.

Unique limestone structure: old substrate. Unique limestone features are remnants of earlier habitat conditions, formed over time from precipitation and weathering of the limestone substrate, and influences of vegetative growth (Figure 138 to 140).

Figure 138. Various limestone structures. Cell photos.

Figure 139. Round limestone structure. Small tree likely once grew within.

Figure 140. LAQI WPT 16, close-up. Limestone bowl with blooming *Ipomea* indicator emerging from a substrate crevice.

Cell photos were taken throughout the study site during the research period to document landscape changes (Figure 141 and 142).

Figure 141. Landscape cell photo of Redland soil area of Unit 2A: April 13, 2019 post-fire (upper), and February 9, 2020 with grasses (lower).

Figure 142. Unit 2A broader landscape image: April 13, 2019 (upper), and February 22, 2020 (lower) to show ground cover vegetation recovery.

Traditional Ecological Knowledge

Traditional ecological and community knowledge of the PR ecosystem, and the open-pine habitat of the S FL region was examined through the a) review of archaeological information, b) early naturalists records, and c) an informal community and expert opinion questionnaire completed during this research.

Traditional use of plants; traditional artifacts and clothing incorporating native plants.

Native American descendants of S FL are represented through today's Seminole and Miccosukee Native American Tribes (Weisman, 1999; Milanich,1998). The Seminole and Miccosukee Tribes are sovereign governments with sovereign lands. An independent Seminole group, unaffiliated with the Seminole government, is also recognized.

A review of archaeological artifacts and records from early native American life in S FL provided insight on the use of specific native plants of the open-pine and PR habitat. Native plant species are observed as food sources; in baskets, tools, and medicines; and displayed in clothing and tapestry (FL Museum 2020; University of Florida 2020; Milanich,1999). Symbols or representations of fire or lightening were not found in the artifacts and records reviewed in this study. This is not meant to conclude that fire was not used or was not of some value in the lives of native Americans in S FL. But, representation in ancient symbology, art, tools, and other artifacts that could be associated with landscape fire, or the use of fire as a tool for farming or habitat care, was not recognized in the information reviewed. This was not a comprehensive review.

Examples of S FL plants with recorded traditional use include *Zamia, Liatris*, and Palmetto species (a-c below):

a. *Zamia pumila* (Coontie) (FL Museum, 2020; University of FL 2020) (Figure 143).

Figure 143. Coontie, *Zamia pumila*, at study site, November 2, 2019. Growth after February 2019 fire. Cell photo.

Native coontie is a primitive cycad species, considered a “living fossil” (Culbert 2010). It is a fire dependent PR species with an underground stem that can withstand fire. The coontie is the sole host plant for the *Eumaeus atala* butterfly larvae (Culbert 2010). While not abundant, new, healthy growth of individual coontie plants was documented at the site post-fire (Figure 143). Figure 144 is a grater tool used in making flour from coontie (FL Museum 2020).

Figure 144. Coontie grater, Seminole, wood, perforated iron, glue, mid-20th century, west central Everglades, (exhibition no. 93512). (FL Museum 2020).

b. *Liatris tenuifolia* var. *quadriflora* (Blazing star).

The purple blooming *Liatris*, a native PR plant species, has been connected to use by the Miccosukee in treating illness (Austin 2015) (Figure 145).

Figure 145. Blazing star, *Liatris tenuifolia var. quadriflora*, blooming in quadrat LAQI 44, October 5, 2019. close up UAS image 11' altitude.

c. *S. palmetto* (sabal palm; cabbage palm).

Various PR native palms and grasses were used in the production of basket products (FL Museum 2020) (Figure 146 to 148). Figure 147 is a Miccosukee packet basket of palmetto stems and leaves, made in 1942 by Mary Tommie, and collected by John M. Goggin (collection number 3933-92925). Also in Figure 147 are three Miccosukee/Seminole baskets of split palmetto stems (upper: basket tray, 1939; [collection number 92917]; lower left: basket sieve, 1939 [collection number 92907], and lower right: basket tray, early 20th century [collection number 92903]) (FL Museum 2020).

Figure 146. Palms from above, study site, August 2019. UAS image. 11’ altitude.

Figure 147. Pack basket, Miccosukee, palmetto stems and leaves. Three baskets: Miccosukee/Seminole, split palmetto stems,

Figure 148. Basket, Seminole, sweetgrass, cotton thread, palmetto fiber, early 2000s, (2006-20-1).

The incorporation of flowering plants was observed in the following traditional tapestries (FL Museum 2020) (Figure 149, a and b).

Figure 149. a) Bandolier bag, Seminole, ca. 1830s-1840s, (E-598). b) Bandolier bag, Seminole, ca. 1830s-1840s, (E-603).

Early naturalist notes.

The existing works of early naturalists in S FL provided brief notations of species occurrence, habitat conditions, and a general timeline of PR condition and habitat loss (Table 9). These notations were cross-referenced to historical aerial imagery time-frames (Figures 124 to 133) and are considered in the Discussion.

Table 9. Early timeline of habitat loss in S FL PR

Reference Date	Notation Referring to S FL PR
1929 (Smith 1929)	Description and photographs reporting on the loss and degradation occurring to the S FL PR habitat. Blaming habitat loss on homes, drainage, and fire (used to clear lands for settlements and agriculture). A report on the absence of once-abundant fern (*Sphenomeris clavate*, Wedgelet fern) that once "*lay in areas of frequent fire*" in the Homestead, FL region at the "eastern edge of Long Pine Key" (now in ENP; very near location of study site). Habitat impacted due to home development. [Note: The Wedgelet fern is currently reported on the list of species present in ENP, and is not reported as present in the study site (IRC 2021)].
1943 (Davis 1943)	"…mainly intact"
1962 (Robertson 1962)	"…under severe threat"
1967 (Alexander 1967)	25-yr. tropical hardwood study: From 1940 to 1964: "Complete conversion of PR to hardwood hammock due to fire suppression"
1999 (DeCoster et al. 1999)	"10 % remaining PR."
2010 to current 2020 (FNAI 2010)	"2% or less remaining PR."

- There was consistency across the literature of specific indicators such as: *Zamia* (Coontie) and palm species: Numerous references noted the use of coontie by indigenous communities as a flour; archaeological artifacts of tools for making flour from Coontie (Weisman 1999). Snyder et al. (1990) reported on the small, commercial use in Miami for coontie flour (refer to Figure 144). Palms had various uses, including as fiber material in making baskets (Figure 147 and 148).

- There was a clear description and understanding from early naturalists such as Harper (1911; 1927); Small (1929); and Davis (1943) of the specific characteristics of the PR ecosystem: open pine, expanse of grassland and diverse forb ground story with an open and sparse shrub (mid-layer) that is predominantly palm; limestone substrate; and the presence of fire in the system as an active driver in creating the observed PR habitat.

Community and Expert Opinion Questions

Fourteen individuals were requested to respond to a PR Community Questionnaire (Figure 150). Individuals were local, private non-governmental, academic, Tribal, County, State, and Federal representatives familiar with the PR ecosystem, and including community experts of the Turks and Caicos and Bahamas PR systems. Seven responses were received. One of the responses was completed via a telephone interview and another in person. Participants were informed that results would be compiled, with individual contact names kept private. A summary of the questionnaire responses is provided below.

<u>Ecological Knowledge Questions:</u>

Introduction: Hello. The following questions are designed to capture local knowledge and understanding, to be informal, and used in addition to published research. The questions are being provided to local community members, researchers, and land managers that have association with the pine rockland system. This valuable community-information is to be used cumulatively, with recently collected and existing data, research, and published literature, to holistically examine and assist in answering the question of "What is 'healthy' pine rockland?". These questions are also one step in describing establishing an approach to assess healthy indicators and status of other under-studied and/or endangered habitats. These questions are included as part of my December 2018 PhD dissertation research, "Ecosystem Condition Evaluation Process: Above and beyond the complex, critically-endangered pine rockland ecosystem", George Mason University, Environmental Science and Policy.

Instructions: Please answer these questions as if you are being personally interviewed. Please provide brief answers but long enough to feel you have provided the answer you want. Answer the questions based on your own expertise, background, and understanding. Do not do further research or consult with others as you complete these questions. Your answers are to reflect your own professional, personal, and/or traditional knowledge of pine rockland. Please answer each question in how you interpret that question. There are no right or wrong answers. Again, these questions are meant to be answered impromptu; I am interested in your perspective, and opinion. Thank you. Note: Your name and identity will remain confidential and will not be shared or included in the results.

1. What makes Pine Rockland, pine rockland?
2. Describe what is "effective or good" fire for pine rockland . How much of local knowledge, experience, and scientific research or data contributes to your answer/opinion to this question?
3. Do you have any information to share on the role of fire historically in this area?
4. Do you have any stories or knowledge on unique species and their functions in PR? For example, an interaction of one or more species, or a particular use of a species?
5. Please provide one to three examples (indicators, measures) of what "healthy" PR is (such as like human – use of pulse, HR, body temp. to identify health).
6. Does an umbrella species (or species-suite) exist for pine rockland? Such as, if that species (or species-suite) is "taken care of", then PR is "taken care of"?

Please provide a brief 1-2 sentence description about yourself in terms of the local community, conservation, or your environmental role or job position:

Layne Bolen, GMU, FWS; Dissertation questions, December 2018.

Figure 150. PR Community Questionnaire.

Summary of questionnaire responses:

1. What makes PR, PR?

"Diversity, fire".

"Limestone substrate and vegetative community".

"Monospecific pine overstory, no mid-story, diverse understory with palms shrubs, herbaceous plants with very high alpha diversity at fine scales. Frequently burned."

"Sometimes people with profit in mind try to imply that a PR is "degraded" to the point where it is no longer restorable. Reasons like "disturbed substrate" or "invasive species" are cited. But even "degraded" parcels may have PR species persisting for yrs., above ground and in the soil seed bank."

"An ecosystem for which the foundation species is a tropical pine (in our situation, *Pinus caribaea* var. *bahamensis*) growing on partially exposed öolitic limestone bedrock in low areas (under 5m in elevation above sea level) constitutes a PR in Turks and Caicos Islands…which includes also the population that grows on sandy substrate without surface öolitic limestone bedrock..." In some areas, although the pine has been lost…the remaining species composition constitutes a remnant PR and, in some cases, pine could be reestablished there."

"This is a fire-successional habitat occurring on limestone substrate, with a canopy of pine trees and a very diverse understory. Without fire, the hardwood species grow larger and take over the pines, shading the understory and eliminating the diverse herbaceous plant flora, making more litter, more humid, moist and shady."

"Originally looked at it from perspective of trees: like the north forest community". "Substrate". "Short (low to ground) understory". "Preserves have different characteristics."

"All the S FL PR preserves are different; Along the S FL öolitic Rock Ridge, there's a… change in soil composition."

"All PR based on elevation; soil deposited layer; pine trees; saw palmetto".
"grassy" ground layer is important - but not all (areas) have that; some have more herbaceous ground cover."

2. **Describe what is "effective or good" fire for PR. How much of local knowledge, experience, and scientific research or data contributes to your answer/opinion to this question?**

"Fire to meet the needs of species; specifically, for croton and species to support butterfly species and for opening up PR habitat to allow movement and dispersal."
Main issues: "Not enough fire and not burned at best times."

"Frequency matters more than individual fires…fire acts as a process not an event. A bad fire would be a fire reintroduced into a long-unburned stand that burns duff and kills overstory… Frequent fires make each induvial burn less dramatic and more predictable."

"Good/effective fire is ANY fire. Everything is so fire suppressed. There is an ideal (prescribed fire in spring, done in a mosaic to leave unburned patches). But worrying about those details right now is like treating a hangnail on a patient while ignoring their stage IV cancer. First, we need regular fire. Then we can worry about perfecting the process."

"Low level/ground fires that burn linearly through the ecosystem, combusting needle duff and grasses/ sedges, while girdling broadleaf woody species constitutes good, effective fire. Occasional flare-ups of sawgrass or palm are acceptable, but fire climbing into the pine canopy is not; that becomes destructive to the habitat's integrity". My understanding of fire…comes from both formal prescribed fire techniques and management training …but also from generational cultural knowledge of the importance fire plays…There is a solid understanding…that PR only flourishes with regular non-catastrophic burning."

"Historically the PR burned due to lightning strikes at the end of the dry season/ beginning of the wet season when the dry ground would be ignited. The FRI is around three to ten yrs. to maintain PR."

"Fire has to carry. The "crazy little shrubs" (*tetrazygia*, locust berry) also carry the fire (act as fuel) need something contiguous to carry fire (fuel), but also need patchy (limestone, low spot) microclimate."
"Now have postage stamp PR (fragmentation), but fire has to be patchy even at a small scale."
"More frequent fire: three to seven yr. rotation. Will have open areas for several yrs. then get leaf litter, debris, and vegetation growing in too dense."
"Loose open soil a component."

“Seasonal: target fires at times for fire to target hardwoods (end of rainy season) …regrowth from November on, will burn, but shrubs not going to burn.”

“Need to maintain open characteristic: “tweak” that seasonally…in a window before too much fuel becomes dangerous (practical matter).”

3. Do you have any information to share on the role of fire historically in this area?

“…species in PR are adapted to frequent fire. Charred pine has been recovered from Pleistocene relicts…we understand how fire functions now, spotty information from the past is less important than how fire functions now.”

“Fires used to change the shape of the landscape and the boundaries between plant communities. But now that is all set-in stone - or literally set-in pavement, really. Dynamic boundaries are now static, which makes frequent Rx fires even more important because the loss of PR species happens more quickly when boundaries don’t move. There is no fire to knock back advancing hardwoods.”

“There is historical knowledge of the Lucayan (island Taino) people having set fire to pine areas deliberately in hunting game. Later during the Loyalist period (1789-1840) the pine yard (Turks and Caicos) was not usually burned deliberately, but was known to have burned. In more recent history, the pine yard was not usually deliberately burned but escaped fires from slash-and-burn agriculture were not stopped…it was understood that the ecosystem rebounded quickly from fire and it did not harm the trees. In some areas…burned prior to timber harvest to make removal of trees easier. Since the impact of the pine tortoise scale insect in the early 2000s, the fire regime has altered dramatically. High numbers of dead mature trees and fallen trunks cause higher intensity, longer-burning fires that are catastrophic in the habitat. Patchy survival of pines means that fire is excluded from a lot of former pine habitat as the broadleaf habitat doesn’t burn as readily.”

“Sadly, for the fragments of habitat that remain near houses, they are rarely burned except by arson occasionally.”

“I know there historically was fire in the system.”

4. Do you have any stories or knowledge on unique species and their functions in PR? For example, an interaction of one or more species, or a particular use of a species?

“There is lots of reports of medicinal plants from Bahamas, names like strongback, love vine, etc. imply their usefulness. Probably the most important species is the overstory pines, they are the foundation species and provide the fuels that maintains the fire that maintains the biological diversity."

"…I'm not sure where to start with this one…I have gradually come to appreciate how important (yet underappreciated) graminoids are to PR…We tend to look at dicots with their colorful flowers but the grasses and sedges are hugely important not only for diversity but also for carrying fire."

"Our PR is known to have nine species of ectomycorrhizal fungi that interact with pine; seven apparently only with pine. Of those, two are apparently endemic to the Caicos Islands and one is believed to be a newly described species. The fungal diversity of the PR is something we are only beginning to understand as it is a largely invisible world. One of our rarest endemic plants, the Caroline's rock pink *Stenandrium carolinae* favors habitat on the margin between PR and broadleaf forest. It is highly resistant to fire and sun exposure, but prefers the dryer substrate of the broadleaf forest."
"… *Senna Mexicana var. chapmannii*, the Bahama senna, a plant with foliar nectaries and protective bodyguards (ants and other predators), hostplants to sulfur butterflies. *Senna spp*. are well known for their use as laxatives and anti-worm remedies in many cultures."

"Miami tiger beetles; in very few PR areas: a predator less than cm in size: relies on open, sandy space from fire about every three to seven yrs."
"Bartram's (*hairstreak butterfly*) - uses new growth post-fire."

"Sabal and saw palmetto: sabal palms really a problem, because of changes hydrology in the system" ... From field research: "perfect" composition for PR is approximately 25 percent sable palm and saw palmetto…seeing approximately 95 percent in some areas."

"Populations of *Amorpha* (Crenulate leadplant; native PR) at the north end of transverse glades, S FL (A.D. Barnes Tropical Park)."

"Native bee (there is also an exotic one) oil collecting Centrid bee... Locust berry: host plant for FL Duskywing…*Lantana involucrate*: native wild sage; blooms all yr. round and used by butterflies."

5. **Please provide one to three examples (indicators, measures) of what "healthy" PR is (such as human use of pulse, HR, body temperature to identify health).**

"Presence of an overstory of pines, frequent fires, few invasives."

"Coverages of grasses is well over ten percent. Coverage of palms, pines, and hardwoods should each be under 25 percent."

"A. Intergenerational population of pine - mature, seeding trees and seedlings and saplings present in some numbers with proper tree density - trees separated by a minimum of 2m so that at maturity their crowns do not overlap but may touch (as was the situation before the scale insect introduction).
B. High genetic variation - representations of all known genetics plus some not yet found.
C. Pine growing in low and high areas of the habitat; both in flood-prone holes and on rocky outcroppings (overall less than 1m difference in elevation but demonstrating diverse situational survivability)."

"Openness - sunlight getting to ground…little accumulation of litter - small litter depth - as found in places fairly recently burned…Large number of species of native understory plants."

"a) Bare ground - patchy.
b) Trees – approximately 200/ac. Mature canopy, varying ages of trees.
c) Some percentage of saw palmetto and grasses to carry fire through the midstory.
d) Understory: biodiversity. Thin layer. Secondary successional habitat."

6. Does an umbrella species (or species-suite) exist for PR? Such as, if that species (or species-suite) is "taken care of", then PR is "taken care of"?

"The pines. Also, some of the charismatic microflora such as deltoid spurge, *Galactia,* other rare and endemic species."

"I don't know but I don't think so."

"In Caicos… pine /Caribbean pine as a foundation species is our main indicator species. The seven pine-obligate ectomycorrhizal fungi species would also be umbrella species."

"PRs have more than 200 species that can be found in their understory, some seen at most sites, others only at a few sites."

"Some consideration for: bobcats and fox as larger umbrella species…Grazing animals for seed dispersal."

"Same answer as given in question 5: a. Bare ground – patchy.

b. Trees – approximately 200/ac. Adult canopy, varying ages of trees.

c. Some percentage of saw palmetto and grasses to carry fire through the midstory.

d. Understory: - biodiversity."

Of the seven responses, two came from individuals working at the local-community and private capacity, one from a county agency, two from individuals associated with FL state agencies, and two from individuals from two different Federal agencies. The Seminole Tribe environmental representative informed the PI that the Tribal representatives could not divulge information about Tribal resources, and could not provide input; As members of a sovereign government, the Seminole environmental managers were not at liberty to provide information on the Seminole resources or management processes. No responses came from repeated emails and phone calls to water quality/natural resource representatives in the Miccosukee Tribe. The reason for this lack of response may be due to the greater presence and resource attention of the Miccosukee Tribe in the western Everglades and Big Cypress National Park in southwest FL, outside of the PR habitat.

In a summary of the questionnaire responses, primary responses for Question 1 included, "fire," "pine canopy," "limestone/substrate/sandy soil," and the "herbaceous flora," One responder recognized the "soil seed bank" in the persistence of the PR habitat. Question 2 responses for "good fire" included, "frequent," "low-level," and "seasonal" fire. Other responses were "opening up PR habitat," and "light fuel to carry 'non-catastrophic' fire," One response stated the "value of patch fire even in small preserves/sites." The predominant responses for "bad" fire were "no fire." or "not enough fire," with a mention to "off season" fire. For Question 3 responses, historical fire was, overall, understood to be an integral component of the PR system, as it is today. One responder commented on the fragmentation and loss of "dynamic (landscape) boundaries" for the system, referring to the need to work (burns) within the strict boundaries of the PR habitat, now surrounded by an urban environment. Other comments referring to current/today's fire compared to historic mentioned that a) the loss of large, mature pines (due to disease in the Caicos) producing heavier fuels rather than the typical light fuels of the PR system, which result in more intense, longer-lasting fires, and b) how fire functions today are more important than how it functioned historically. In response to Question 4, some examples of unique species functions and interactions were the Bahama senna plant (*Senna spp.*), a host plant to sulfur butterflies, and which possesses nectar-secreting glands that play a defensive role against ants and other predators. The *Senna spp.* are also known in "many cultures as laxatives and anti-worm remedies"; Miami tiger beetle as an indicator needing open, sandy space; a role of the native, oil-collecting, *Centris* bees being studied; and the value of graminoids (grasses) for carrying fire. The emerging study in the interactions between ectomycorrhizal fungi and pine was also mentioned. Interestingly, the highly-invasive, parasitic love vine in S FL was mentioned to be believed in the Bahamas as having potential medicinal use. In Question 5, example indicators for a "healthy" PR system included: pines of different ages; grass abundance greater than ten percent; palms, pines, and hardwood each with no more than 25 percent abundance; frequent fire; diverse understory; and open, patchy characteristics. In Question 6, other than "pine" being identified by two responders, no single, specific species was identified as an umbrella species for PR; One of those responders also included, “charismatic microflora (deltoid spurge, other rare and endemic species).” The “ground cover,” or “diverse set of understory species”; and a “suite of umbrella species” was identified by respondents. One responder recognized “some percentage of palmetto.” And one responder stated they did not think that an umbrella species or suite of species exists for the PR system.

Lastly, in further examination of what a “healthy” ecosystem is and its view in traditional cultural knowledge, the PI attended the Pacific Islands-Climate Adaptation Science Center (CASC) November 17-18, 2020 virtual Climate Adaptation Summit. The Summit was attended by more than 200 interdisciplinary scientists, land managers, and community members and focused on the scientific community work and needs to sustain the health of the Pacific Islands. The topic of bio-cultural conservation was presented by Christian Giardina, USDA Forest Service, with the concept that it (the habitat) is “not just the place” but also the “functional” resources as defined by the culture that matter (for example, waterflow), and that it is necessary to consider “cultural function as part of a cultural place.” This may not necessarily be a function recognized for its biological role in a system but a function that is culturally-identified and holds particular cultural significance.

In summary, historical, even ancient traditional knowledge, may or may not be consistent with the current ecological knowledge and value-sets of local community cultures. In this case, descriptions of TEK, or the incorporation of TEK into current conservation practices were not directly obtained from the Tribal community or government through questionnaire responses or direct communication. The review of archival resources provided information and perspective on specific species and PR habitat descriptions. Traditional use, such as with the Coontie, grasses, and palms indicates the persistence of these species over time. Their continued presence can potentially indicate the functional persistence of the PR ecosystem. Based on the individual questionnaire responses, there is consistent agreement on the importance of the herbaceous ground cover and the PR system's dependence on fire to maintain the appropriate proportion of vegetation classes and diversity. See "*Discussion, Research Question 1*" for further integration of the UAS imagery and TEK results.

Identified PR Indicators

Indicators identified were those species, habitat types, or functions used to evaluate the condition (health) of the PR system. A summary of these indicators is provided in Table 10. The synthesis of results from the a) UAS flight survey imagery; b) LAQI indicators; c) field-work (ground cover evaluation); d) community questionnaire and TEK; e) literature review; and f) supplemental remote imagery data was used to identify the most effective set of measurable biotic or abiotic indicators to assess the S FL PR system. The use of multiple data-sources follows an approach used by Pellant et al. (2018) and Herrick et al. (2019), which supported the integration of historical reference and remote imagery, and qualitative use of scientific experts and data, for the landscape assessments.

Table 10. Summary list of identified PR indicators

Indicators	Functional connections, Notes
fire	Critical functional indicator; temporal. Importance in management is understood. Challenge is to get enough fire on the ground and build this into the community. Short FRI prevents mature hardwood; maintains open mid-and ground-story. Ideal stand-maintaining regime of low intensity, 3-7 yr. FRI, surface fire, (but if not possible, then at least any fire is better than no fire), heterogenous, patchy.
open-midstory	Produced by fire; allows for herbaceous ground cover. Shrubs remain small; relatively young; low density of adult shrubs: approximately 25% palmetto spp; lack of mature hardwood with thick branches and height over a few ft. Spatial component.
herbaceous ground cover; suite of endemic forbs	The diverse suite as a whole is a critical functional, temporal indicator for PR health; spatial indicator of open-gap canopy (available mixed sunlight and space at ground layer). Condition is an indicator of midstory shrub condition (% abundance/maturity). If there is no fire, suite is getting buried, smothered, and compromised, but a diverse suite of endemics species/seedbank may still persist below the overgrowth depending on time since last fire. Species redundancy. Many fire-dependent species. Functional interactions as host spp., for pollinators, and dispersal via insects. Observed rapid recovery (emergence) of herbaceous species immediately post-fire.
rapid emergent growth post-fire	Functional; temporal component. Rapid vegetative emergence post-fire; Repeated (three to seven yr.) fire needed to allow this fire-recovery-growth-turnover cycle to persist. Seed bank and system persistence.
rapid forb turnover	Functional; temporal component. Rapid vegetative emergence post-fire; Observed rapid turnover of forbs, system persistence; redundancy in forb species.
grasses	Critical species indicator of open pine/grassland system. Under-represented (low distribution and abundance) due to lack of fire or incompatible fire regime (too hot; off season) that allow shrubs and/or heavy palmetto to displace.

Indicators	Functional connections, Notes
limestone substrate	Critical microclimate function and structure; characteristic component that defines system function. Remaining PR sites have this indicator, but in many sites, it is broken and not intact; has experienced chopping and break up from early agriculture. Edaphic condition include: calcium-carbonate pH; rapid draining; crevice-structure that holds detritus and provides moist microclimate. Thin litter layer over substrate.
pine canopy density	Spatial component; Lack of fire allows pine to expand. Fire keeps canopy healthier. Past forestry practices result in denser pine than ideal. Need variable age classes; Need to keep ratio of pine that allows relatively thin adult canopy, mixed sunlight, and space for open ground layer. Source of fine fuels and ground cover material.
deltoid spurge	Possible valuable key indicator of system health. Some Federally listed species. One of first PR plants to return post-fire; provides low-level ground habitat/mats. Potential relationship to pollination with ants. Ants are commonly observed throughout the spurge.
croton and butterfly	Host plant/butterfly functional group. Croton is a multi-prong, critical indicator -Supports primary food for endangered butterfly larvae. Croton health is tracked closely in fire management. Support croton health via fire regimes = support for PR ground cover.
ground litter layer	Spatial; functional; temporal. Accumulated organic ground material of mostly pine needles, dead vegetation and fine soil layer over, and incorporated with the limestone substrate. Plays a critical role in the quality (moisture and structure) of the ground layer microclimate, and as available fine fuels. The layer is variable in distribution, abundance, and depth based on pine canopy, and FRI.

Putting It All Together SEW - Workbook

The various raw data spreadsheets, flight logs, and image processing logs were included within or hyperlinked to an Excel SEW. This is an active workbook (prototype) for the evaluation. The SEW works as a catalog or repository for the resources, data, and work efforts used during the research. Currently, the SEW includes spreadsheets of a) UAS flight logs and blank template; b) UAS image processing log and blank template; c) field assessments and blank template; d) remote imagery resource list with hyperlinks; e) indicator information sheet; f) indicator trend worksheet; and g) a summary list of types of data sources used in the evaluation (UAS imagery types, other remote-sensed imagery, existing plant survey data, questionnaire) used with hyperlinks to the References file.

The images acquired from the flight surveys, and the under-the-canopy flights are the first comprehensive imagery set for the S FL PR system. The newly-devised UAS methods and resulting images effectively contributed detailed information on the characteristics and functioning of the diverse herbaceous ground cover indictive of healthy PR habitat. The LAQI quadrat imagery and in-field quadrat assessments complemented one another as methods for tracking single indicators and standardized plots. The comprehensive existing literature, supplemental historical remote sensed imagery, and input from local community experts were used in a synthesis-fashion to evaluate PR habitat from a historical and current perspective.

DISCUSSION

Introduction

The purpose of this research was to develop systematic methods for an ecosystem evaluation of the critically endangered PR habitat using site-scale UAS mapping, and newly developed (under-the-canopy) survey methods for understanding ground cover diversity and health; and existing available, efficient, and affordable resources such as imagery data, published works, local knowledge, and expert input.

This chapter contains a summary of the key findings and discussion to respond to the study's research questions and with context to the existing literature. Practical applications and limitations of the study are discussed. Suggestions for future research are presented.

Summary of Key Findings

This section includes a summary of the key findings and discussion of the study's research questions.

Research Question 1.

What is the most effective set of measurable biotic or abiotic indicators to assess the S FL PR system (including at least one functional group; and one spatial, and one temporal component)?

The set of indicators (Table 10) were those determined to be representative measures of the diversity and function of the S FL PR ecosystem at the study site. Following the method-synthesis concept presented by Herrick et al. (2019) and Bowman et al. (2015), the set of biotic and abiotic indicators were selected through the synthesis of the study's results (UAS imagery, field work, questionnaire responses), and the comprehensive review of the literature and archived remote imagery. This set of indicators or descriptors of healthy condition for the PR ecosystem identified through this study is not meant to be an exclusive list.

Existing information and literature specific to the PR habitat were used for the selection of indicators, as well research on fire-adapted, open-pine/grassland systems, and the principles of functioning CASs (Levin 1998), including redundancy (Parr et al. 2014; bi-stability (Ghadami et al. 2018; Dantas et al. 2016); recovery rates (Scheffer et al. 2009; Rietkerk et al. 2004), and fire as a positive-feedback loop (Pulla et al. 2015; Bowman et al. 2016).

The set of indicators (Table 10) includes: an implemented, variable fire regime (Kelly and Brotons 2017; He et al. 2019; Noss 2018; Slocum et al. 2003); diverse, herbaceous ground cover of forbs and grasses (Robertson 1962; Veldman et al. 2015); rapid (efficient) post-fire vegetative growth and recovery (Ghadami et al. 2018; Bond and Keeley 2005); presence of diverse set of endemic plants (Schmitz et al. 2002; Trotta et al. 2018; DeCoster et al.1999) with specific functional roles in insect food sources and dispersal (Tilman 2014; Funk et al. 2017; Soliveres et al. 2016); rapid turnover of forbs (Ames et al. 2017; Parr et al. 2014; Snyder et al. 1990); sparse midstory shrub layer

(Smith 1929); limestone substrate (Schmitz et al. 2002; Crow and Ware 2007); ground litter layer (Possley et al. 2014; Slocum 2003; Harper 1911); and open pine canopy (Carr et al. 2009; Snyder et al. 1990).

UAS site imagery of the fire footprint from the February 2019 wildfire provided information on the a) quality of the fire, including canopy involvement; b) fire intensity; and c) area burned across the site (Figure 26 and 27). Image classifications of the UAS flights identified the spectral signatures of PR habitat types. The filtering of classes (such as the pine canopy) in the image classification analysis, highlighted for comparison, specific group types, including, "ground cover vegetation," "limestone," and "pine needle" (Figure 45 and 46).

Post-fire vegetative recovery at Unit 2A is illustrated in selected t-c orthomosaic images (Figure 26, 27, and 33). The "healthy" open midstory that existed post-fire is identified in unsupervised classification imagery illustrating grasses, exposed limestone, and ground cover vegetation (Figure 34). This is compared to an unsupervised image of overgrown vegetation (Figure 36), identified with heavy midstory and ground vegetation, and a lack of exposed limestone and grasses.

The early, post-fire emergence of the herbaceous ground cover vegetation was documented in initial LAQI flight images (Figure 76, and 77), and the in-field evaluations. The UAS flight surveys acquired 12 days post-fire, also identified new growth (Figure 26), as many PR forb species' have seed banks spurred by fire.

The fast-ecological strategy (Ames et al. 2017) of small plant turnover in the herbaceous vegetation was documented in monthly LAQI surveys of the PR ground cover

(Figure 73, 67, and 68). Results illustrated the dynamic nature (rapid recovery and turnover), growth/blooms, and diversity (multiple group types) of the herbaceous ground cover as it occurred post-fire. The turnover of *Galactia* and the replacement with other forb species is an example of the redundancy within the herbaceous ground cover (Figure 73).

The high PR plant diversity and endemism were evident in post-fire habitat imagery (Table 3; Figure: 47-52; 69-74; 78; 81-83; Appendix 8), supporting the literature on the diversity of the PR herbaceous ground cover (Possley et al. 2008; 2014; FWS 1999; FTBG 2017; Trotta et al. 2018).

Fire suppressed units with dense, midstory hardwood overgrowth resulted in fewer functional habitat group types identified in image classifications, with those group types having a similar monotypic, pixel spectral signature (Figure 36, 56 and 57). The herbaceous forbs and grasses were observed under the dense overgrowth; however, they were being smothered and did not appear to be thriving. This is consistent with observations by Robertson (1962) on how the "low pineland flora" was subdued and inconspicuous in areas unburned for three to four yrs.".

The different PR habitat group types were discriminated in UAS imagery by their unique pattern and design as well as their spectral signatures (Table 5). Exposed limestone was identified based on its distinct bright white color and irregular structure. Grasses, such as the Redland soil/grass area, tended to have a brown/green shade and a smooth texture (except for individual grass tufts like that seen for gamma grass); shrub and plants were more vivid green with a rougher, irregular texture compared to the grass

(Figure 29, 97, 113, and 114). Palmetto was very distinct in the images, both in its teal/turquoise shade and unique frond pattern (Figure 100 and 115). UAS imagery illustrates the difference in a PR site with a lower abundance of palmetto (Figure 27 and 35) compared to a PR site with a high density of palmetto midstory (Figure 100).

Overlaps between the spectral signatures (pixel values) of PR habitat group types were typically illustrated in the resulting image classification rasters (Figure 39 - 43). This was an expected result because of the highly-vegetated and diverse system, with numerous vegetation types and similar (green) vegetation shades. The results of the in-field and LAQI ground cover abundance estimates (Table 6) also identified mixes of class types (such as "mix of pine needles and exposed limestone"; or "mixed forbs and grasses") more often than monotypic group types ("exposed limestone"; or "grasses"). The "pine needles mixed with the herbaceous forbs" was a persistent ground cover class type identified in the in-field and LAQI abundance estimates (Figure 46 and 58). This suggests that a mix (or associated group) of ground cover group types (ground cover mosaic) (grasses and forbs mixed; pine needles with limestone) is likely a more accurate representative indicator or measure of ground cover condition than a single group type. The mix of ground cover group types is a healthier condition than a monotypic indicator, and the overlap in spectral signatures in the UAS imagery, is an accurate reflection of the mosaic of the PR habitat cover. The UAS site imagery did not capture below-ground and fine organic soil conditions within the limestone crevices. However, the yr.-long, monthly, post-fire LAQIs and field-quadrat evaluations documented a relatively stable, moist environment (microclimate) within the limestone structure, and a persistent, but variably-distributed, layer of accumulated organic material at the substrate surface.

A persistent, shallow ground cover layer of mostly pine needles, with other vegetation litter over the substrate was identified in the UAS imagery and in-field evaluations, supporting the observations made by Harper (1911). The "pine needles" classification group was consistently identified in the ground cover imagery, although its spectral signature/color (pixel value) distinctly shifted from the burnt, bright orange signature (burned, consumed fuel source) seen in images soon after fire, to the light brown/light orange shade of freshly shed needles seen in later images (Figure 61 and 64; Table 6).

The UAS image classification documented a high level of variability in the strength (level of presence) of both the "pine needle" and "dead branches/twigs" (ground litter layer). The LAQI images, and in-field quadrat evaluations, particularly, provided detailed information on the variability in the depth and distribution of the ground cover mix across the site, and unique spectral signature for this layer depending on conditions (time since fire; amount of accumulation; age of materials; and moisture content) (58, 60-61; 64-66; Table 6). The ground litter layer played a role in moisture retention and structure of the ground layer microclimate, supporting recovery and growth of the herbaceous ground cover. Its depth has been identified as a measure of ground layer condition in relation to time-since-last-fire (Possley 2014). The "ground litter layer" was not expected to be identified as a key indicator for system health, but was included based on the findings.

Continuity in the long-term presence of specific, native PR species (*Zamia, Liatris*, and palm species) was identified after synthesizing information from the, records of indigenous use (Figure 144,147 and 148; Florida Museum 2020); early naturalist reports (Harper 1911, 1927; Smith 1929; Davis 1943); qualitative expert reporting (Austin 2015[*Liatris*]; community questionnaire; and the remote imagery, and in-field evaluation results. Questionnaire responses described healthy PR habitat as consisting of palm species existing in an open midstory ("composition of sabal and saw palmetto"; "not heavy abundance [less than 25 percent abundance]"); this same characteristic (an open understory and a sparse presence of palmetto shrub species), was consistently mentioned by early naturalists when describing the PR ecosystem. The use of palm species in the Seminole culture remains a current practice (Figure 149). *Zamia*'s longevity as an ancient cycad species, in the PR system is, to some degree, likely associated with its significance as a (geoxlye) grassland species, with fire-resistant, underground storage organs (Maurin et al. 2014). Plants of each of these species were identified in the study site (Figure 143, 145, 146).

The suite of characteristic features (indicators) of a healthy PR ecosystem (Table 10) were consistently identified or illustrated across the multiple-data sources utilized in this research: literature review; archival information; early naturalist reports; qualitative, expert reporting; rare plant site-data; in-field evaluation; and remote imagery (Figure 38, 55; 91; and 94). Historical reporting (Harper 1911, 1927; Smith 1929; Davis 1943) captured the understanding of the multiple features and complexity that constitute a healthy PR ecosystem. These same biodiverse features were identified in the research's imagery and in-field quadrat evaluations (Figure 39; 143; 146). The historical naturalist observations (Table 9) and aerial imagery (1950-2019 time-series) together record the habitat loss and fragmentation continuum for S FL PR that persists today. The aerial imagery documents the over 50-yr. time-series of land conversion around the Navy Wells study site.

Questionnaire responses about unique PR species and their functions (Question 4) were varied and intriguing. One response identified the potential relationship between multiple fungi species and pine; others identified native bees and host plants. Based on existing literature and knowledge (USFWS 2018; Questionnaire response) (Figure 70), the croton (*c. linearis*) plant and larval butterflies (particularly the Bartram's hairstreak butterfly [*Strymon acis bartrami*] for its use of new growth after a fire), was identified as an example functional group in the PR system. Deliberate in-field searches and closeup visual inspections were made for insects and other biotic life during this research. A variety of insects and insect life (cocoons, egg masses, webs) was regularly observed functioning within the PR habitat, almost inconspicuously, at the mid- and ground-story levels (Appendix 8). For example, ants, identified by Austin (2015) as a potential pollinator of *Deltoid* spp. in PR, were observed as commonplace among the deltoid plants in the study area. Rather than a single function group, Soliveres et al. (2016) identified multiple-pollinators as a potential driver to understory function. Further research on the role of pollinators, or multiple-pollinators, as healthy PR indicators is warranted.

As mentioned, the indicators (Table 10) described in this research are not meant to be exclusive. Their identification as key components to a healthy PR system are based on the synthesis of existing information, imagery, and field work. For this reason, the resulting list of indicators, except for "ground litter layer", was, in some form, expected. The list, however, extends past the presence or absence of the indicator in the system but also describes each indicator in terms of relevant functional, temporal, and spatial components. The herbaceous ground cover's presence*, and proper functioning* (rapid return post-fire; rapid turnover of forb species) is a key indicator for PR system health. Additionally, the "list" of indicators is to be viewed as an interconnected web of conditions, rather than a linear list. It is the interactions between various indicators (such as the mosaic of the herbaceous ground cover, litter layer, and limestone; or the redundancy of the forb species) that support complex system function.

Research Question 2.

How will the UAS platform be best utilized to capture visual data on a) specific indictors or ecosystem conditions of characteristic PR habitat that include ground cover (grassland/glades), solution hole, and pine forest, and b) varied PR ecosystem states (post-burn; wet-dry season) in select fire management units, and based on time since last burn, for use in assessing spectral signatures and structural components of vegetative condition?

The small UAS quadcopter with a RGB sensor was the predominant platform used for this research (Figure 8 and 11). The UAS was used for yr.-long, monthly, a) automated flight surveys (Table 1), b) LAQI (Table 4), and c) ad hoc flights. This research is the first year-long, monthly collection of UAS imagery acquired for S FL PR habitat, providing baseline data for evaluating the system.

The automated flight surveys and ad hoc images were developed into t-c orthomosaics, and calculated VARI and unsupervised/supervised image classification rasters were processed from the orthomosaics (Figure 26, 31, and 37). Fewer pictures were acquired for ad hoc flights than for the flight surveys, so resulting ad hoc orthomosaics were smaller and useful for examining ground cover composition (Figure 92). LAQI flights produced single, t-c .jpg images, which were used for time-series comparisons (Figure 67 and 68), and processed into supervised/unsupervised image rasters (Figure 55, and 58) to classify herbaceous ground cover diversity.

The overhead, automated flight surveys were specifically used in this research to acquire site-level baseline habitat data, post-fire imagery, and imagery of distinct features of PR habitat for use in evaluating the system (Figures 112 to 115). High-resolution data of the fire footprint, including canopy effects, were acquired soon after the arson wildfire (Figure 26 and 29), and repeated monthly flights resulted in a full-yr. of baseline imagery of post-fire recovery (Figure 27 and 33). Pre-and post-fire UAS imagery of a prescribed burn was also acquired (Figure 99, 100 and 102). Images of distinct features or conditions of the PR system acquired with the UAS platform include: a) solution hole (Figure 112); b) grassy area (Figure 113); c) hardwood, shrub overgrowth (Figure 114); heavy palmetto midstory (Figure 115); and e) invasive species (Figure 30 and 100).

The detailed fire footprint imagery (Figure 26 and 29) is informative for understanding the impacts and recovery of a system. An advantage of the UAS platform for this research was efficiently flying repeated flights over the fire footprint in real-time. The post-burn UAS imagery provided data on the fire quality such as aerial extent, burn pattern (patchiness), and intensity (He et al. 2019). Repeated flights over time provide a composite of fire imagery history that addresses landscape heterogeneity and patch dynamics, identified in promoting diversity within a fire-dependent forest/grassland system (Parr and Anderson 2006; Hiers et al. 2009; Kelly and Brotons 2017; Bowman et al. 2016).

Heavy fuel loads (such as dense midstory shrub) are associated with decreased diversity (Ratajczak et al. 2012; Slocum 2003). In the post-fire UAS imagery, differences in the effects of fire were observed between Unit 2A (an area with hardwood thinning a few yrs. before the fire) (Figure 26) and Unit 2B (an area without hardwood thinning and with heavy shrub) (Figure 29).

The resulting VARI images of PR habitat were particularly effective for illustrating the fire footprint (Figure 26 and 28); and highlighting specific PR features, including a large solution hole (Figure 111), and invasive shrubs (Figure 30 and 97). The ad hoc VARI images were also found useful for discriminating specific spectral signatures of understory group types, such as shrubs and limestone (Figure 90 and 91). The VARI range and color palette were adjusted manually to highlight aspects of an image. The ranges of six automatically-calculated VARI flight survey images of PR Unit 2A acquired through the yr. post-fire, are provided in Table 2.

Schweiger et al. (2008) found spectral diversity as predictive of ecosystem function as taxonomic and phylogenetic diversity. The unsupervised and supervised image classification process to classify and evaluate habitat types was highly effective with UAS imagery of PR habitat (Cruzan et al. 2016, upland prairie/vernal pool; Lisein et al. 2015, deciduous tree habitat). This research is believed to be the first study to develop image classification rasters for PR habitat. Specific spectral signatures for the PR group (habitat) types were classified with the UAS imagery (Table 5; Figure 31, 33, 36 – 38, 98, 100, and 102). Both the unsupervised and supervised methods were used on the Unit 2A, February 2019 orthomosaic to compare results (Figure 26, 31, and 37).

The classified image rasters identified a considerable degree of overlap in some spectral signatures, particularly as green vegetation returned to the fire site (Figure 39, 40, 42, 43, 45, 46). This overlap, lack of statistical separation, of signatures was expected in a diverse habitat. During the classification process, as much of the pixel values were retained as possible with the intent to retain and document the diversity and "mosaic" of the PR habitat. Despite the overlap of signatures, the specific group types were distinguishable.

The LAQI and ad hoc flights were manually flown, under-the-canopy, using methods developed for this research to study the PR herbaceous ground cover, where most of the diversity of the system resides (Refer to Methods, "*UAS LAQI Flights*"). Initial works studying understory diversity with the UAS platform have been with a top-down approach (Getzin et al. 2012, forest understory; Bargaram et al. 2018, and Dong et al. 2020, canopy patch metrics). With an open pine canopy like the PR system, it was possible to view the understory and ground cover with the UAS imagery. However, rather than interpreting ground cover through the canopy or based on the characteristics of the canopy, the under-the-canopy methods successfully acquired unimpeded, detailed imagery of the understory. Elevated and panoramic images of the PR habitat under-the-canopy were also acquired (Figure 94 to 96).

The repeated LAQI quadrat sampling, and time-series sets of images, were used to capture the diverse ground cover and monitor habitat and species changes (Figure 55, 57, and 58). Supervised image classification of the single, LAQI images was utilized in the identification of ground cover group types, including fine fuels (Figure 59 to 65). Although the ground litter layer (mostly pine needles) was not an original focus of this study, the UAS ground cover imagery was recognized for its effectiveness in identifying and monitoring the abundance and distribution of this litter layer.

Although the comparison in results between the LAQIs and in-field quadrat evaluations was a limited exercise, the results indicated the ability for LAQI images to estimate ground cover composition and abundance, or to be used in conjunction with in-field quadrat evaluations to assess ground cover. The variation found between some of the reporting suggests a need to broaden this exercise to build standardized and reliable assessment methods. The LAQI data supplemented the field-evaluation data, but it was most effective for estimating abundance of ground cover types when the two resources were used conjunctively (Refer to *Summary of Key Findings, Question 4*).

The LAQI method is a rapid and efficient overhead- photographic method in which numerous photos can be rapidly acquired in a standardized and repeatable process. The use of this method can prevent or minimize foot trampling of the ground cover compared to on-the-ground photographic methods. The use of the UAS is a much more efficient and less-destructive process in acquiring numerous images for tracking habitat changes than the process of physically setting up a photograph tripod and camera on-site. Information obtained from the LAQI and in-field quadrat assessments contributed to the resulting list of identified PR indicators (See Results, "*Identified PR Indicators*").

The flight survey, adhoc, and LAQI images were used together to present detailed information on a specific area or species (Figure 87 and 91). The vHR UAS imagery filled a gap between the coarse resolution of satellite imagery (Richards and Gann 2015) and ground surveys. While more limited in range, detailed subtleties of the habitat, and detections of rapid ecosystem changes (Murray et al. 2018) can be obtained with UAS imagery compared to larger satellite and aerial data (Figure 131 to 133) (i.e., small scale with detail).

There was limited use of the UASs equipped with a m-s RedEdge camera, and a Survey 3 MAPIR camera with a m-s OCN filter. Resulting images from these flights included orthomosaics, NDVI index (Figure 119), and a supervised classification of a OCN derived orthomosaic (Figure 118). The resulting images with the OCN filter are promising for its use in discriminating PR canopy from ground cover (Figure 117).

The UAS platform was best utilized through efficient, regular and repeatable sampling, providing data that is difficult to acquire with manned aircraft, or through in-situ work alone. The new methods for manual flights under the canopy resulted in detailed images of the diverse PR mid-story and ground cover habitat. The UAS platform provided scaled imagery results from the site-level to individual species indicators. Integrating real-time, specifically focused remoted-sensed imagery for describing ecosystem condition supports habitat and ecosystem protection policies (Corbane et al.

2015; Veldman et al. 2015; Noss 2013). It is critical to recognize the contribution small parcels and fragmented habitats still provide in global biodiversity (Wintle et al. 2019). Remote sensing technology, including UASs, increases the capacity to assess these smaller areas, and synthesize and incorporate that information into global assessments.

Research Question 3.

What are the capabilities of UAS sensors in discriminating characteristic limestone substrate ground cover and hydrologic conditions of PR (within an (a) immediate- and (b) weeks- post-burn time interval)?

The PR limestone substrate is one of the most defining characteristics of this system. The exposed limestone, and its distribution, was clearly-discriminated in the PR UAS flight survey and LAQI imagery (Figure 26 and 40), primarily based on its white color, and reflective nature, as well as its "rough" textural appearance (Figure 48). The classified imager rasters were an effective method for identifying the "exposed limestone" habitat class type (Figure 31, 32, and 34), LAQIs (Figure 55), and ad hoc images (Figure 90 and 92). The exposed limestone class was generally identified as a smaller signature in the flight survey supervised classification images and graphs than other classification types (Figure 39 to 46), but was still distinguishable. Exposed limestone was identified in VARI images, and heat palette as bright blue, but could not be definitively separated from low ground cover of the same pixel color without field verification or LAQI or ad hoc comparisons (Figure 28 and 90). One contributing factor in the ability to definitely separate the substrate signature was the broken condition of the substrate from historical tilling.

The greatest extent of exposed limestone (some mixed with ash) was visible in the immediate post-fire images of Unit 2 (Figure 26), and as expected, became less distinguishable, based on time since last fire, as vegetation and fine fuels (pine needles) returned to the site (Figure 40, 43, 53, and 68). The discrimination of exposed limestone in the image classifications decreased, and began to be identified mixed with pine needles and/or grass (Figure 73 and 89). Exposed limestone was not identified as a group type in overgrown sites (Figure 36 and 56). Like ground cover litter, exposed limestone was highly variable across Unit 2 (Table 6).

The LAQIs and adhocs were particularly useful in discriminating limestone substrate using visual comparisons of time-series images, comparing early (post-fire) images of exposed limestone to later images, with the limestone covered with ground vegetation or litter (Figure 67,78, and 88). Vegetative return and growth, including at the species-level, were examined in relation to the underlying substrate using the vHR, small-scale LAQIs and adhocs (Figure 68, 72, and 91). The deltoid spurge (Figure 79), and poinsettia (Figure 136), two calcareous-tolerant plants in the *Euphorbia* group (Stern et al., 2016), were documented in the PR study site.

The UAS RGB sensor had the capability to discriminate the structural and functional characteristics of the PR limestone substrate. Results shows the limestone crevices, holes, and depressions of weathered limestone described by Small (1929) and Harper (1911) (Figure 138 to 140). The ground cover imagery results illustrate broken limestone, the historic impacts from agricultural tilling at this site (Figure 49). While weathering of substrates is a natural process, weathered and broken substrate are known to increase absorption (Laliberte et al. 2103). Further study is warranted on whether the tilled, crumbled PR substrate in this study site could be experiencing increased weathering rates and if in turn, could be influencing plant diversity or other PR functions. Results indicated however, the substrate was functioning effectively at the study site, supporting herbaceous plants in areas of organic litter and soil accumulation, and tree root and shrub growth among the substrate (Small 1929) (Figure 70, 71, 73,80, 91, and 137).

Although the S FL PR habitat is a mostly flat, microtopography (Figure 117), the substrate's spatial complexity of small crevices and holes plays a critical role as a microclimate, providing structure, organic materials/soils, moisture, and the overall edaphic conditions needed for plants and animals at the ground level (Schmitz et al. 2002; Crow and Ware 2007). The limestone structure functions in providing rapid runoff (from heavy tropical rains) and a sustainable, suitable moist microclimate for the recovery and persistence the herbaceous ground cover and seedbanks. Although this active process, per se, was not directly documented in the imagery result, images acquired immediately after rain, including heavy rain, did not show spectral signatures for standing water. Ground moisture conditions in UAS images flown post-rain resulted in slightly different (darker) spectral signatures of the ground cover, primarily related to the damp versus dry pine needle litter. Consistent with existing literature (Snyder 1990; Harper 1911), no standing water was ever observed at the study site; waters drained or were rapidly absorbed, even after torrential downpours or tropical storms.

Pine hammocks and transverse glades do not occur on the study site therefore, data on hydrologic conditions associated with these features was not collected. However, the imagery was acquired of a large solution hole (Figure 111). The heavy vegetation surrounding the solution hole is evident in images, with a distinct shape and spectral color.

The MAPIR OCN filter was used experimentally to determine its ability to discriminate canopy from ground layer spectrally. Flight surveys with this filter distinguished “limestone” and “low vegetation” from dense “pine canopy” signatures (Figure 116 - 118). The OCN filter was found to have promising results. Overhead flights captured ground cover (light blue to green) compared to pink shades of the canopy, but discriminating the limestone and lower vegetation classes required field verification.

Research Question 4.

What survey protocols or combination of protocols are most effective for collecting field verification data?

Ground cover estimated percent abundance assessments were performed monthly in LAQI quadrats (Table 3) following LAQI flights. A detailed description of the in-field quadrat assessment methods can be found in the *Methods* Section.

The assessment protocols and the “In-field Quadrat Assessment Worksheet” (quadrat worksheet) (Figure 18) were modified from Richardson et al. (2013) and Taft et al. (1995). Richardson et al. (2013), used similar vegetation indexes for measuring the relative abundance of ground cover types in a coastal scrub habitat, including open patchy spaces; grasses; herbaceous (non woody) plants; open, patchy shrubs (woody vegetation); and litter and fine fuels. Like PR, the coastal scrub system has an open-patchy, shrub midstory in relation to FRI, and experiences dense shrub (hardwood) overgrowth and compromised herbaceous vegetation due to fire suppression.

The quadrat worksheet (Figure 18) lists the ground cover types and percent ranges for estimating abundance in PR habitat. The ground cover types were refined for the PR habitat through site visits to the study site prior to the assessments, expert input, and literature review. These group types were later supported through the UAS image classification results. Cell photos of quadrats were collected simultaneously with the in-field assessments and LAQI flights. The worksheet data was transferred to an excel spreadsheet (An example is shown in Appendix 7). Results were used to a) cross-reference LAQIs, b) verify group types in the image classification process, and c) be applied with LAQIs to verify group types and evaluate vegetative changes.

Results provide an overview of monthly abundance estimates for the LAQI quadrats (Appendix 7). Quadrat ground cover group types tended to shift from monotypic groups ("grasses" and "forbs") to group "mixes" ("mix of grasses and plants") as the diversity and complexity of the ground cover returned post fire. The field estimate results verified the variety of ground cover classes identified in the UAS image rasters.

Fine fuels are critical to fire in the PR system (Carr et al. 2009; Harper 1911), and the information on the fine fuels ("sticks/branches", and "pine needles") collected in the field assessments and LAQI images (Figure 64 and 65), helped assess the rate of return of fine fuels to the site post-fire.

Quadrats indicated a high degree of variability in predominant ground cover types as a result of location, as expected in the diverse PR ground layer: Quadrats under pine tended to have higher levels of pine ground cover compared to those in the open areas; quadrats in depressed areas had higher organic (pine needle) layers (still thin) and held more grasses and forbs. The LAQI quadrats were distributed across the site to capture these variations in the ground cover imagery (Figure 48 to 52). Overall, once vegetative growth returned after the fire, each of the quadrats had a variety of the ground cover types present, but with varying estimated abundances and distributions between them.

LAQIs (Figure 81 to 83) and field abundance data (Table 6) was cross-referenced to one another. A prototype comparative exercise was performed between in-field assessment results and LAQI image reviews using the same assessment protocol. Table 6 provides the effects of the comparison exercise between in-field evaluations and LAQI assessment reviews of the same quadrats (Figure 81 to 83). LAQIs hold promise in supplementing in-field verifications or being used with in-field assessments for ground cover evaluations. The LAQI reviewers needed to build familiarity with the nadir aspect of the images.

The in-field quadrat assessment protocol and worksheet developed in this research specifically for the PR habitat, can be modified and transferred to other ecosystems. The benefits to the protocol are the efficiency and compatibility with the LAQIs. Collecting monthly, yr.-long data was important for capturing the rapid re-growth and changes in species composition, abundance, and turnover that occurred post-fire, as well as through the growing season. The most ideal protocol would be to document pre-and post-fire data. Pre-fire data was not possible in this case due to the wildfire however, the results of this research now contribute to baseline data. Suggestions for improvement of the in-field quadrat verification process include: a) familiarizing evaluators to the vegetation classifications, as a group and before the evaluations to develop consistent search images of habitat types among the evaluators, and b) clarifying instructions in using the ranges for estimating percent abundance.

Both the in-field verification and LAQI flight methods provide detailed and, complementary quadrat information. The-in field quadrat evaluations effectively estimated PR ground cover types, but the synthesis of data from the two sources provided the most accurate quadrat evaluations.

Research Question 5.

To what capacity can the necessary flight protocol and procedural safety plans for UAS surveys be developed into a comprehensive resource document for use in planning and implementing ecological surveys using UAS imagery?

Components of this study included the development of the 1) UAS PASP for Navy Wells (Appendix 4), and 2) an excel worksheet prototype for the research evaluation called the System Excel Worksheet (SEW) (*Methods* Section; Figure 25).

This PASP was developed in collaboration with the DOI Remote Pilot Program, following a DOI PASP format. The PASP and the UAS flight methods developed from this research can be transferred to other habitat evaluation research projects. The PASP is a separate process and document from the research plan. The PASP follows legal FAA airspace rules, use of appropriate platforms, FAA training and certification, safety risk assessment and mitigations, communications, and landowner approval. There was an advantage to being both PIC and PI for developing flight and safety protocols, but it is not necessary as long as the PI communicates the research goals and desired outcomes (for using the UAS platform) to the PIC; who will develop the PASP in coordination with the PI. The PI has oversight over the research, but the PIC, has authority over the flights. It is critical to discuss and establish roles and responsibilities during the planning phase.

Daily flight plans (and flight logs) were implemented consistent to the PASP. While it is necessary to coordinate with the landowner on the PASP, it was also useful to coordinate regularly on the flight plans about any local and site-specific knowledge that could influence the flights. Any UAS flights being incorporated and implemented within a research project should be accompanied by an independent UAS PASP. As the small UAS is incorporated as a tool in habitat evaluations and other conservation work, it is important to continue to cultivate a culture of safety and responsibility in its use.

The SEW worked as a catalog for the resources, data, and work efforts used in the research. It was developed during the course of the study, into a comprehensive resource workbook for planning and implementing the evaluation. The SEW consists of Excel spreadsheets that include: a) UAS flight logs and blank template; b) UAS image processing log and blank template; c) field assessments and blank template; d) remote imagery resource list with hyperlinks; e) indicator information sheet; f) site indicator trend worksheet, and g) a summary list of types of data sources (type of UAS imagery, other remote sensed imagery, questionnaire) used with hyperlinks to the References file.

Practical Applications of the Study

This research, by design, was meant to be practically applied. The resulting UAS imagery is baseline imagery data for the critically endangered S FL PR habitat. The research results directly contribute information about S FL PR system. Information and data resulting from this research can be applied to other areas of S FL and global PR habitat, and supplement the listed-PR species recovery plan (USFWS 2018). More broadly, this research is a comprehensive method for habitat evaluation and developed new UAS methods that can be applied to other systems.

Ecosystem evaluations, such as this one, focus on the system, as its own entity, and on the system-wide (CAS) characteristics of the landscape-mosaic, function, and diversity; beyond that of a single species. A purpose of the evaluation process is to apply the results of a local ecosystem evaluation (like that for PR habitat) towards larger-scale global ecosystem conservation efforts such as the IUCN Ecosystem Risk Assessment program. In the IUCN ecosystem risk assessment program, assessors select the variables to estimate environmental degradation and determine change. Little guidance is provided to assessors at the local level in how to best select and use indicators for quantifying change (Rowland et al. 2018). Often it falls to the local community or regional entities to collect and submit the detailed ecosystem information needed for use in a broader global risk-assessment program. This research provided a practical, multi-source data, process for selecting indicators and identifying variables that consider CAS processes and help describe a "healthy condition". This process can be used to evaluate change or degradation of the endangered PR ecosystem, and can be applied to the broader global risk assessments. The process and methods used in the site evaluation have applicability to other locations and systems.

In addition to knowledge exchange with the SEW, a standard assessment and reporting form could be used at each habitat location (such as the different global locations of the PR ecosystem in S FL and the Bahamas), and compiled into a global ecosystem report. A standardized reporting form is useful for fragmented (like PR), or widely dispersed (island) ecosystems. Individual, on-the-ground program efforts, or research and management actions at a site would not change or be made to be identical across all areas, sites, or preserves. However, a standard report would be used for key indicators' status and habitat evaluation at each preserve, and then submitted into a comprehensive EER for the global PR ecosystem. This EER would be incorporated into global ecosystem evaluations, and risk-ranking programs, such as the IUCN Ecosystem Risk Assessment Program.

The various methods and information sources used in the research advocate for collaboration and information-sharing efforts. Collaborative efforts were found more effective in producing comprehensive results. The research applied a practical method for incorporating and considering various stakeholders, and conservation and management efforts.

The UAS platforms are relatively available, affordable, and easy to use, and provide high-quality, high-definition images. The LAQI and adhocs images are more easily shared than larger images, and can be used for illustration and outreach. The UAS images fill a gap in scale between field-monitoring and broader resolution aerial and satellite imagery for habitat evaluations, and the efficiency in collecting UAS imagery can provide real-time imagery results. Processing the images is possible with publicly-available Apps and software programs. The UAS methods developed in this research are particularly applicable to other open canopy, grasslands. The UAS was an excellent tool for capturing PR diversity.

A full yr. of monthly, post-fire UAS surveys of the fire footprint were acquired of PR habitat in the Navy Wells study area, a preserve designated by the State as one of the highest quality remaining PR habitats in S FL. The UAS flight protocols developed in this research can be effectively incorporated into a fire program to continue to capture pre-and post-fire imagery that can be developed into a PR habitat "fire-history catalog." The heterogenous, patchiness of a fire is a key component in variations over time in vegetative recovery, diversity, and distribution. UAS imagery of the fire footprint can help build the specific description of a fire, such as its aerial extent, burn severity, intensity, and degree of patchiness of that fire. This fire information, ground observations, and additional information on the FRI, and even a hardwood-thinning management return interval (MRI) can be compiled into a database. There were various sources of information about the history of fire events on the study site, but these were often incomplete or had disparate data. A descriptive database of fires and hardwood removal events on a PR preserve is imperative for gaining a perspective and understanding the cumulative (positive) effects of the long-term fire program. The research's UAS component (planning, flight methods, processing) is applicable and effective tool for site management. Repeatable flight surveys of multiple fire footprints of the same site create a time-history of variable fire and the landscape's resulting patch mosaic and heterogeneity. Multiple fires over multiple yrs. can be easily documented with UAS platform. Fire description data, using the UAS imagery as one source of data, can be standardized across the global PR preserves, and used as a means of data sharing, and communications for comparing the results of fire management in the PR system.

The innovative, under-the-canopy flight methods and detailed imagery of the PR ground cover (where most of the diversity occurs) can be applied to other open canopies, and grassland systems. The high-quality LAQIs have practical application in assessing details of ground cover habitat; as a complementary data source to field evaluations, and developing time-series sets of images at the species-level. LAQIs can provide supplemental information in coordination with comprehensive field surveys. Time is saved that would otherwise be spent in field surveys, and images create an archival record.

Ad hoc flights are helpful to focus on and illustrate a specific location or ground cover condition. The orthomosaic images are smaller than flight surveys and provide direct imagery of the ground cover, below the canopy. The ad hoc imagery is faster to process and easier to share than larger orthomosaics. They are manually flown and this allows flexibility in the flight route. A disadvantage to adhocs is that they are not repeatable flight paths. It is feasible, however, to fly a larger, single ad hoc flight or fly numerous flights and batch them in processing, to obtain a larger ground cover orthomosaic image.

Limitations to the Study

This research aimed to document and capture the detail (complexity) and diversity of the PR habitat, particularly its herbaceous ground cover, referring to multiple indicators and spectral imagery to classify habitat characteristics. While the CAS principles (such as, redundancy, feedback loops, alternative stable states) were considered in this evaluation, measuring the full "complexity" of a functioning CAS is difficult (Queirós et al. 2016), and measuring the complexity of landscape patch dynamics over space and time, like that modeled by He et al. (2020), was beyond the scope of this study. However, this study documented the capability of the UAS to capture detailed fire-footprint imagery of the PR habitat that is informative on the extent, heterogeneity, and patch complexity of the burn. The under-the-canopy images were also used to document the heterogeneity, and functioning diversity of PR system post-fire.

The typical method used with the unsupervised/supervised image classification process is to simplify (habitat) groups. In this research, the greatest amount of spectral diversity (pixels) was retained to maintain characteristics of site diversity. This method however, resulted in a high amount of spectral signature overlap between the habitat group types that could confound the full spectral range of a single group. This was overcome by filtering similar groups in the analysis so a single signature could be reviewed more clearly.

The RGB imagery is, in general, reported to be more difficult than m-s data, for discriminating group classes during the image classification process, and spectrally provides only 3-band images compared to the multi-band sensors. The RGB sensor was the sensor available for this study, and the most-commonly found on small UASs available to the public. The resulting high-definition RGB orthomosaic images were found effective for the identifying distinctive group types in the image classification process, and with the VARI developed for RGB data. There was limited availability to use the m-s camera, and OCN m-s filter (In January 2020, the DOI remote program was grounded by the Administration; by March 2020 covid prevented further flights), but the RGB sensor was planned to be the primary sensor for this study, with back-up platforms available if needed. The m-s data was supplemental, but small UASs with m-s cameras are now becoming more available and affordable,

This research was limited to S FL PR habitat, at the preserve-level, and other global PR habitat locations were not studied. The study site was selected because of its status as one of the largest remaining and State-designated, exemplary PR habitats. UAS flight imagery was acquired from two other S FL PR locations, and the PI had completed site visits and spent time in numerous other SL PR preserves. The global distribution of the PR ecosystem was addressed in this study through the review of literature; the community questionnaire, and attendance at the 2020 global PR Working Group Annual Workshop.

The UAS imagery was collected in sometimes less-than-ideal environmental conditions, such as bright sunlight, wind, high heat and humidity, and variable overcast conditions, common of subtropical S FL weather. Flying UAS flights in varied conditions were deliberate to test the methods and imagery results working in real world land management conditions, however, this resulted in some flight images with too much shadow, sun reflection, or blurriness that prevented complete image alignment. This was overcome by completing numerous and redundant flight surveys. The UAS platform had limited range capability compared to manned aerial and satellite platforms, however the UAS platform provided an additional layer of high-definition, detailed site data that was not available with the broad-scale remote imagery. The use of multi-scaled imagery complemented one another as information contributed to the study.

The limestone substrate was identified as a critical indicator for a healthy PR system. This research examined the role of the limestone substrate, particularly structure, in providing a system-wide microclimate for support of the recovery and persistence of the herbaceous ground cover. A study of the specific edaphic factors of the limestone substrate (such as within-and-below ground soil moisture, and substrate pH) was beyond the scope of this research.

The use of multiple data sources and types required or was best achieved through collaboration. Best efforts were made, but not all parties were able to, or comfortable with sharing information or working collaboratively. This was the exception more than the rule, but it limited access to some information. Questionnaire responses were thoughtful and informative. Disseminating the questionnaire more broadly may have resulted in additional, beneficial feedback. The use of multiple data sources can take more time and be a more complex process than a singular data source evaluation. The resulting evaluation, however, is diverse and comprehensive.

Suggestions for Future Research

Additional work is needed on the multiple trophic food webs and functional groups in PR habitat, including multiple pollinators as a potential driver to understory diversity (Soliveres et al. 2016); results from this study and literature suggest the PR habitat plays a role as a diverse "pollinators habitat." Responses from the community questionnaire cited future works needed on functional group interactions of PR plant species and native bees, and the potential relationship between pine species and multiple endemic ectomycorrhizal fungi. Directed PR plant studies could examine the potential for *deltoid ssp.* as being ant-pollinated, and the unique nature of the white top sedge (*Dichromena floridensis*) as insect-pollinated (sedges are typically wind-pollinated [Austin 2015]). The microbial aspects of the limestone substrate are also underexplored. Also, further research is warranted at Navy Wells and other PR preserves on the newly discovered PR endemic, PR Trapdoor Spider (*Ummidia richmond*).

Overall, the PR substrate is understudied, and additional research pertaining to the substrate and its relationship to PR vegetation characteristics is warranted. Mapping surveys (using a laser scanner-equipped UAS) of the PR microtopography are suggested to understand further its relationship to plant composition (Alexander et al. 2016). Such research can include how the substrate's structural alterations from agricultural tilling may be influencing the a) herbaceous ground cover in terms of composition, and partitioning; b) draining and filtering of rain, and c) below-ground limestone and fine soil characteristics.

Research is needed on below-ground plant traits and the influence of nutrients and mineral (phosphorous) on plant diversity. The *Zamia* (Coontie) plant was not specifically tracked as an indicator, but *Zamia* plants were documented recovering in healthy condition in the post-fire habitat, and are well-recorded in TEK records. The plant is a primitive species, and its persistence in the PR system deserves further examination. New research exploring the presence of geoxyles, plants with underground, fire-resistant organs (such as *Zambia*), in the PR system may add to an understanding of the contribution of these fire-adapted species to system diversity and resilience. Further research is suggested for other more inconspicuous, non-listed, native or endemic PR species, as potential indicators of system health.

Two future research topics specifically applicable to the diversity of the PR ecosystem are 1) pyrodiversity (how variable fire is promoting diversity); and 2) phylogenetic diversity (PD) and PR endemics (how PD relates to the biodiversity of herbaceous ground cover; continued work of Trotta et al. [2018]).

Additional long-term research on variable fire, patch mosaic burning, and heterogeneous landscape in promoting PR biodiversity could be continued using the UAS platform. This research would include acquiring, processing, and documenting imagery of multiple fires on a preserve over time. Modeling of pine canopy gap metrics could provide further information on its relationship in influencing herbaceous ground cover diversity and integrated with data on litter layer depth and FRIs.

Chronic fire suppression is having a direct and deleterious effect on the remaining S FL PR habitat; endangering this system’s existence. A new fire program model that is able to be implemented in an urban environment is needed. Modified and non-traditional fire plans, or new, and even unorthodox (legal) approaches for addressing this issue need to be considered and tested with multi-disciplinary input. Field experiments could study the effectiveness of smaller, more numerous fires ("garden fires") in place of the typical prescribed burn regimes that plan for full parcels or unit fires, but that are very difficult to implement due to permitting approval and need for ideal weather (wind/heat) conditions in the urban environment. A "small/smaller" fire concept may be effective in small fragmented systems, and urban areas where burning numerous acres in a single fire is prohibitive. These "garden fires" would be easy to plan and manage and result in a heterogeneous patchy burn pattern. UAS flights could be easily-applied to this work. The on-the-ground research and testing of new ideas must be coupled with programs for local policy, adjacent landowners, community outreach, and the incorporation of fire education programs into grades schools. Direct projects to place fire-on-the-ground in PR are critical.

Additional research is possible using the large volume of UAS imagery acquired with this research, including additional batching of orthomosaic flight survey images, further image classification processing, and the creation of LAQI time-series images. Multiple ad hoc flights flown in a single flight session at a site and batched in the Agiosoft processing can be used to develop a full-scale orthomosaic of the PR ground cover. Advancements in UAS image processing using object-based image analysis (OBIA) (shape and spectral factors), or structure from motion (sfm) (3D [3-dimensional]) methods can be specifically applied to ecosystem evaluations (De Luca et al. 2019;

Laliberte et al. 2011). New UAS platforms (micro-UASs), and sensors (LiDAR and m-s), and filters (such MAPIR OCN) can continue to be applied to research of natural, more complex ecosystems. Agricultural or crop survey technologies are often transferrable to ecosystem research and should be considered.

Research is needed on the climate effects to grassland systems. This would include specific effects of atmospheric carbon dioxide (CO_2) on woody species abundance, implications to grassland species composition, and the classification and evaluation of global grassland biomes.

This study focused on ecosystem-level condition. Continued ecosystem evaluations and research are warranted to address the ongoing risks to these systems. Results can be applied to the development of a much-needed national ecosystem-protection policy. Future research examining practical methods of evaluation and management could be applied on a broader scale, beyond that of the single ecosystem, in which the management of the S FL PR would be linked to other associated S FL natural communities and regional ecosystems (such as sand scrub, coastal strand, and isolated wetland systems); many also being threatened. Like multi-species recovery plans (USFWS 2018), the evaluation and management would apply to multiple-ecosystems (a S FL ecosystems management unit). The tools and technologies exist to evaluate and manage at this scale.

Conclusion

This research integrated UAS imagery, field research, and multiple data sources and types, to identify essential indicators of healthy PR habitat, and evaluate system function and diversity. The CAS concepts and processes (feedback loops, recovery rate, redundancy, and alternate stable states) were considered in the selection and evaluation of indicators. Data sources included published scientific data, historical reports, existing remotely-sensed data, fire history, plant survey data, archaeological archival information, and community input.

The resulting set of monthly UAS imagery is the first comprehensive catalog of UAS imagery for the S FL PR habitat. The detailed orthomosaic images were also processed using the VARI calculator, and unsupervised and supervised image classification methods to identify the fire footprint and quality (intensity, extent); PR habitat classification types (spectral signatures); and specific PR features (solution hole, palmetto, grassy areas, overgrowth). Using the heat color palette, The VARI image results, were particularly useful for discriminating the effects of the fire footprint and heavy shrub density. The image classification process identified spectral signatures for vegetation and other PR habitat class types (limestone, pine needles) that were used for evaluation purposes. Individual spectral signatures indicated a high degree of overlap between signatures, particularly for the diverse shades of (green) vegetation. However, an overall distinction of individual group types was possible, and the image-classification graphs were able to provide trend information of specific groups, such as grass, and fine fuels.

Newly developed under-the-canopy LAQI and ad hoc manual flight methods resulted in detailed imagery of herbaceous ground cover mosaic. Image classification processing with LAQI images produced spectral signatures for PR ground cover classes.

Small orthomosaic images of the understory were developed with the ad hoc flights. In-field quadrat ground cover abundance estimates were used to supplement and verify the UAS imagery results, identifying the variability of the PR ground cover group types.

UAS imagery of post-fire diversity resulted in noticeably different and diverse spectral signatures compared to areas with hardwood overgrowth. Numerous and diverse group types were identified in the recently burned units compared to the overgrown units, in which fewer groups and similar (brown monotone) pixel colors were identified. Functional differences in the PR habitat between these two conditions were also discernable. Incorporating regularly flown UAS flights into a pre-and post-fire monitoring program could effectively identify shifts in shrub density, fine fuels, and other site factors for maintaining healthy conditions.

Fragmentation has caused, and is currently causing, the loss of the regional S FL PR ecosystem. However, diversity, endemism, and function persist at the individual preserve-level in the units studied and that had recently burned. Effective temporal, spatial, and functional PR indicators were documented in the post-fire units. CAS functional characteristics of post-fire PR habitat were documented in the imagery results, including the feedback loop of fire and rapid vegetative recovery; heterogeneity (system complexity); and the turnover, redundancy and diversity of herbaceous ground cover species. The fire/herbaceous ground cover feedback loop perpetuates the system, maintaining an open-midstory, and regrowth of fine fuels that supports repeated fire. Fire is the key to persistence of the system, or the system will slowly shift to a novel, less-diverse, and irreversible condition (such as hardwood hammock or invasive monoculture).

Information from the reviewed literature, questionnaire responses, and field observations suggest the potential role of multiple pollinators as a driver to herbaceous ground cover diversity. Limestone is a defining, but understudied feature to this system that warrants further study. Also, to be explored is the potential presence of "underground forests" (underground plant organs), and the role these structures may play in the persistence of the PR grassland system, and potential influences from saltwater intrusion.

The integration of field research and qualitative information (multiple-sources) was found to be an effective framework for developing a comprehensive ecosystem evaluation. The use of historical reports, archived remote imagery, and individual insights contributed to a broader, historical perspective of Navy Wells, and PR system, beyond the current condition and a shifting baseline perspective.

As a CAS, the ecosystem is its own entity. The ecosystem evaluation is meant to focus protection and conservation actions to this broader system scale. Standardized use of healthy, CAS indicators in evaluating and reporting other S FL and global PR preserves can result in a complete global ecosystem report. The catalog system used in this research to manage information and document the evaluation process may be applied to other ecosystems, and contribute information to broader global ecosystem conservation programs.

APPENDIX 1. FEDERALLY-LISTED AND ENDEMIC PR SPECIES

Federally ESA-Listed (FWS) and Endemic (Trotta et al. 2019)

Big Pine partridge pea* - *Chamaaecrista lineata* var. *keyensis*
Blodgett's silverbush - *Argythamnia blodgetti*
Carter's small-flowered flax* (and designated critical habitat) - *Linum carteri* var. *carteri*
Crenulate lead-plant* - *Amorpha herbacea v. crenulata*
Deltoid spurge* (wedge sandmat) - *Chamaesyce deltoidea* ssp. *deltoidea*
Everglades bully - *Sideroxylon reclinatum spp. austrofloridense*
Florida brickell-bush* (and designated critical habitat) - *Brickellia mosieri*
Florida pineland crabgrass - *Digitaria pauciflora*
Florida prairie-clover - *Dalea carthagenensis* var. *floridana*
Garber's spurge (sandmat) – *Chamaesyce garberi* (Engelman ex Chapman)
Pineland sandmat* - *Chamaesyce deltoidea* ssp. *pinetorum*
Sand flax* - *Linum arenicola*
Small's milkpea* - *Galactia pinetorum* Small
Tiny polygala – *Polygala smallii*
Wedge spurge* (sandmat) - *Chamaesyce deltoidea* ssp. *serpyllum*

Miami tiger beetle - *Cicindelidia floridana* (proposed critical habitat designation)

Florida leafwing (and designated critical habitat) - *Anaea troglodyte floridalis*
Bartram's scrub-hairstreak (and designated critical habitat) - *Strymon acis bartrami*

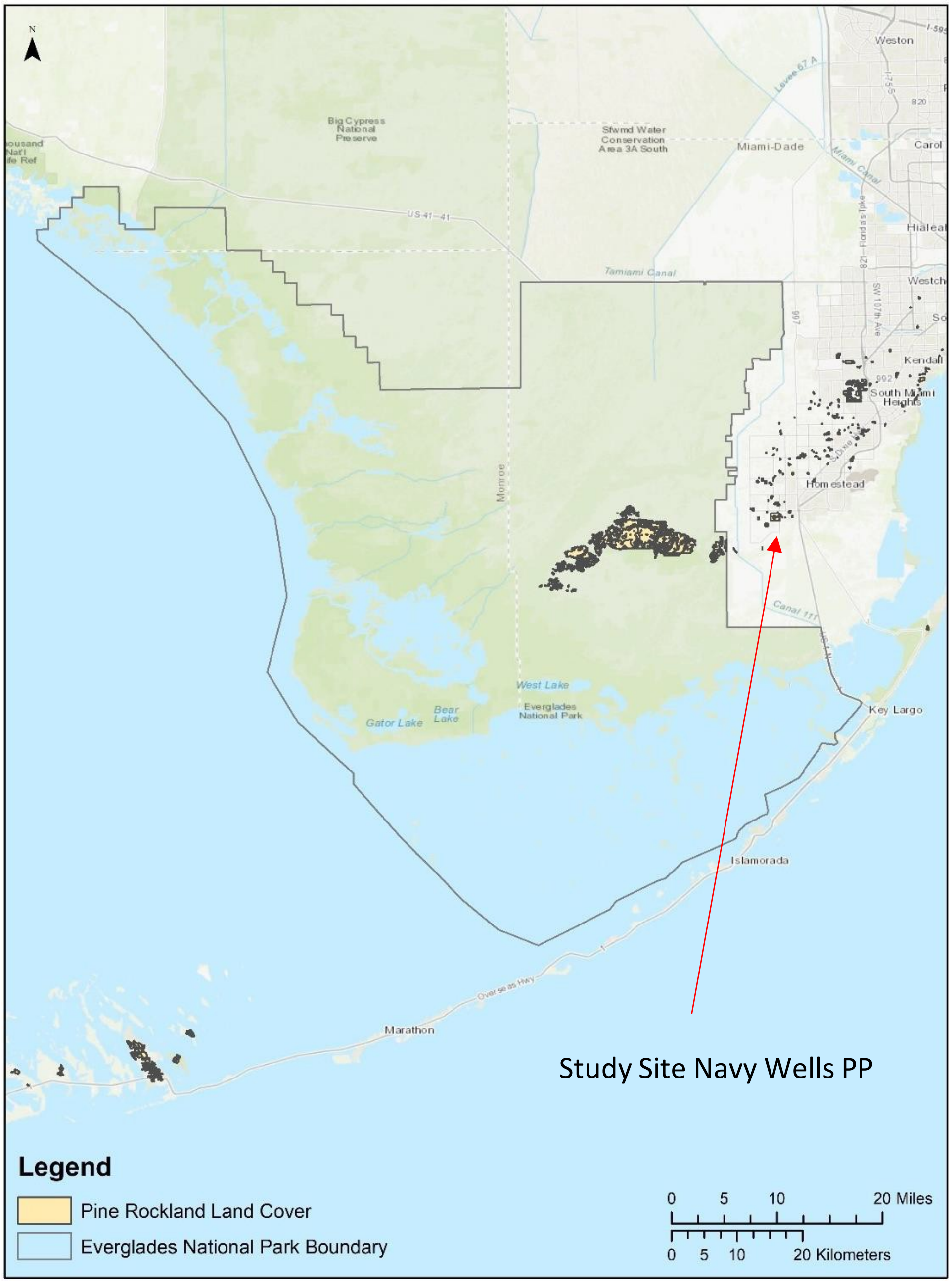
Rim-rock crowned snake - *Tantilla oolitica* (under review by FWS for proposed listing and critical habitat)

*Federally-listed and endemic.

FL PR Endemic Plant Species Phylogeny (FWS 1999; Trotta et al. 2018)

Scientific Name	Common Name	Clade	Family
Amorpha herbacea v. crenulata	Crenulate lead plant	Superrosid	Fabaceae
Brickellia mosieri	FL brickell-bush	Superasterid	Asteraceae
Chamaecrista lineata	Key partridge pea	Superrosid	Fabaceae
Chamaesyce deltoidei ssp. *deltoidea*	Deltoid spurge	Superrosid	Euphorbiaceae
Chamaesyce deltoidea ssp. *adhaerens*	Goulds wedge sandmat	Superrosid	Euphorbiaceae
Chamaesyce deltoidea ssp. *pinetorum*	Pineland deltoid spurge (pineland sandmat)	Superrosid	Euphorbiaceae
Galactia smallii	Small's milkpea	Superrosid	Fabaceae
Lantana depressa	Lantana	Superasterid	Verbenaceae
Linum carteri	Carter's flax	Superrosid	Linaceae
Poinsettia pinetorum	Pineland poinsettia	Superrosid	Euphorbiaceae
Stenari nigricans	FL diamond flower	Superasterid	Rubiaceae
Tragia saxifolia	FL noseburn	Superrosid	Euphorbiaceae
Euphorbia deltoidea Engelm. ex. Chapm. ssp. *serpyllum* (Small) Y. Yang (Trotta et al. 2018)	Wedge sandmat	Superrosid	Euphorbiaceae
Galactia pinetorum Small	Milk pea	Superrosid	Fabaceae

APPENDIX 2. SOUTH FLORIDA PINE ROCKLAND. MIAMI, EVERGLADES NATIONAL PARK; FLORIDA KEYS



APPENDIX 3. LAQI WPT COORDINATES AND DATE CREATED

WPTs

011 2QA 08-MAR-19 9:36:47AM N25 26.478 W80 30.379
012 2QB and 2QB deltoid 08-MAR-19 9:53:04AM N25 26.483 W80 30.368
and 2QB deltoid 08-MAR-19 9:53:04AM N25 26.483 W80 30.368
014 Gamma Grass 08-MAR-19 11:11:06AM N25 26.481 W80 30.356
016 Ipomea 08-MAR-19 11:17:19AM N25 26.483 W80 30.345
018 Thistle 08-MAR-19 11:37:58AM N25 26.498 W80 30.35
020 Locust Berry 08-MAR-19 11:51:17AM N25 26.493 W80 30.343
021 Tetrazygia 08-MAR-19 11:54:00AM N25 26.490 W80 30.339
028 Pineland croton 16-MAR-19 9:11:43AM N25 26.477 W80 30.377
029 Dollarweed 16-MAR-19 10:01:48AM N25 26.498 W80 30.348
Pineland Twinflower 16-MAR-19 10:15:02AM N25 26.497 W80 30.346
031 Galactia p. 16-MAR-19 10:40:11AM N25 26.489 W80 30.340
032 Lantana blooming (was 25) 16-MAR-19 11:45:50AM N25 26.485 W80 30.340
033 Bahama saxhia 16-MAR-19 11:50:19AM N25 26.485 W80 30.337
034 Passiflora suberosa 16-MAR-19 12:43:08PM N25 26.481 W80 30.366
03 Wetland petunia 16-MAR-19 1:51:54PM N25 26.480 W80 30.336
041 Spurred butterfly pea blooming 25-MAR-19 2:51:55PM N25 26.478 W80 30.337 042
biodiverse limestone area near 2QB 13-APR-19 8:58:29AM N25 26.478 W80 30.369 043
white button near 2QA 13-APR-19 9:19:36AM N25 26.483 W80 30.372
044 Thistle C. horrigulum 13-APR-19 12:32:30PM N25 26.495 W80 30.333
047 C. rhododendron 16-JUN-19 8:58:44AM N25 26.509 W80 30.335
048 Walter's ground cherry 16-JUN-19 9:13:31AM N25 26.521 W80 30.354
049 Devil's Potato near 18 16-JUN-19 9:23:48AM N25 26.498 W80 30.349
055 round limestone bowl 27-JUL-19 7:53:59AM N25 26.481 W80 30.346
056 Agalinis blooming 27-JUL-19 9:31:33AM N25 26.516 W80 30.355
063 clasping aster 02-NOV-19 9:06:43AM N25 26.481 W80 30.352
073 blooming thistle -did not flag – took drone images and cell photos (adj to WPT 18)

WPT LAQI date created

WPT	LAQI Date created
011 2QA	24 Feb 2019
012 2QB	24 Feb 2019
and 2QB deltoid	8 March 2019
014 Gamma Grass	16 March 2019
016 Ipomea	16 March 2019
018 Thistle	16 March 2019
020 Locust Berry	16 March 2019
021 Tetrazygia	16 March 2019
028 Pineland croton	16 March 2019
029 Dollarweed	16 March 2019
030 Pineland Twinflower	16 March 2019
031 Galactia p.	16 March 2019
032 Lantana blooming	16 March 2019
033 Bahama saxhia	16 March 2019
034 Passiflora suberosa	16 March 2019
035 Wetland petunia	16 March 2019
041 Spurred butterfly pea blooming	25 March 2019
042 biodiverse limestone area near 2QB	13 April 2019
043 white button near 2QA	13 April 2019
044 Thistle C. horrigulum	13 April 2019
047 C. rhododendron	16 June 2019
048 Walter's ground cherry; furthest N	16 June 2019
049 Devil's Potato near 18	16 June 2019
055 limestone bowl	27 July 2019
056 Agalinis blooming	27 July 2019
063 clasping aster; purple daisy-like	2 November 2019

APPENDIX 4. NAVY WELLS PINELAND PRESERVE AVIATION SAFETY PLAN (IN COORDINATION WITH USFWS)

U.S. Fish and Wildlife Service

Unmanned Aircraft Systems (UAS)

Project Aviation Safety Plan

May 4, 2019; L. Bolen

Navy Wells Pineland Preserve

This document was prepared in compliance with DOI Operational Procedures Memorandum (OPM) - 06, Aviation Management Plans, and complies with FAA, DOI, and FWS policies

Table of Contents

Project Name and Objectives Navy Wells Pineland Preserve unmanned aerial habitat surveys. Collect baseline aerial imagery of endangered pine rockland habitat for use in health assessment.

Justification
Provides real-time, high definition imagery minimizing foot traffic and impacts from ground surveys. Use of aircraft to perform survey is approximately four times faster than a ground survey, or faster, depending on the terrain. Use of a fleet owned unmanned aircraft is inherently safer and substantially less expensive than renting a helicopter.

Project Dates *(NTE 364 days)*
Starting Date: May 29, 2019 Ending Date: May 29, 2020

Location
General Location (attach area map noting project area):
All UAS operations will occur within the boundaries of Miami-Dade County Natural Areas Management Units 1 – 8, Navy Wells Pineland Preserve, Homestead, FL. North boundary: SW 344th St., South Boundary: SW 360th ST.; East boundary: Tower Road (Route 9336); West boundary is agriculture lands.

Project Center Point Coordinates: Latitude: 25° 26' 18.52" Longitude: 80° 30' 24.51"

Airspace Classification (mark all that apply, attach sectional chart noting project area):
☐Class B ☐Class C ☐Class D ☐Class E XClass G ☐Special Use Airspace

Airspace Description (Describe airspace, Military Training Routes, TFRs, SUAs, etc.):
The entirety of the Navy Wells Pineland Preserve is in Class G, uncontrolled airspace, beneath Class E airspace at 700ft. AGL.

Airspace Authorization: ☐COA XPart 107 ☐FAA-DOI MOA ☐E-COA

Comments: All flights will be conducted under FAA Part 107 authorization. NOTAMs will be filed to cover all UAS operating areas, centered at project center points listed above,

Project Area Land Status (ownership)
☐USFWS ☐Other DOI XState XLocal ☐Private ☐Other

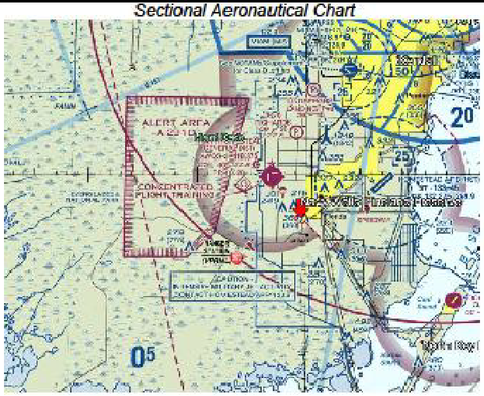
Land Use Authorization:
Sonya Thompson, Miami-Dade Natural Areas Management; 305-582-7444; Sonya.thompson@miamidade.gov.
Unit 1-8 will be flown under the agreement of Miami-Dade County Recreation and Open Spaces Natural Areas Management, Florida.

Adjacent Units #9, 10, and 11 are under the authority of the State of Florida, Florida Keys Aqueduct (FKA) and will not be flown. A courtesy call is given to the (FKA) security gate on the day of surveys so staff are aware we are working on the County site that day.

Location (continued)

Area of Operations Map

Sectional Aeronautical Chart



Projected Cost of Aviation Resources		
Aircraft/Sensors: 3DR Solo UAS with GoPro Hero4, Ricoh GR II, and Sony UMC-R10C cameras FWS owned = $0 Parrot Anafi; DJI Mavic Pro; DJI Matrice 600 Pro; BEV FireFLY6 Pro	*Equipment and Supplies:* Work table, canopy, chairs	*Other:*
UAS Crew Travel: No overnight travel expected.	*UAS Crew OT:* No OT expected.	*Total Estimated Cost:* No cost other than base salaries.

Aircraft

The following DOI fleet UAS will be utilized as the primary aircraft for this project, though other aircraft may be used during the course of this project. All aircraft utilized will be DOI carded.

Type	Make/Model	FAA Registration #	OAS 36-U Exp. Date
☒Rotor Wing ☐Fixed Wing	3DR Solo	FA3W43PATW FA3YMXFNR7	3/12/2020 3/28/2021
☒Rotor Wing ☐Fixed Wing	Parrot Anafi	FA3A7TYYNN	4/4/2021
☒Rotor Wing ☐Fixed Wing	DJI Mavic Pro	FAMWPWM4N	2/15/2021
☒Rotor Wing ☐Fixed Wing	DJI M600 Pro	FA3PW3RXHF	2/21/2021
☐Rotor Wing ☒Fixed Wing	BEV FireFLY6	FA3MR9PF9P	5/21/2020

Payloads/Sensors

☒Go Pro Hero 4 ☒Ricoh GR II ☐FLIR Vue Pro ☐Micasense RedEdge

☒Sony UMC-R10C ☒Sony a6000 ☒Zenmuse X5 ☒Zenmuse XT2 ☐Zenmuse Z30

Pilot(s)

The following DOI remote pilots will be the primary pilots for this project, though other pilots may operate under this PASP. All pilots will be carded by the DOI-OAS.

Remote Pilot 1: Scott Bishaw	Aircraft Qualified to Pilot: Solo, Anafi, Mavic, M600, Firefly	DOI Card Expiration Date: 4/30/21
Remote Pilot 2: Layne Bolen	Aircraft Qualified to Pilot: 3DR Solo	DOI Card Expiration Date: 4/30/21
Remote Pilot 3: Jeff Howe	Aircraft Qualified to Pilot: 3DR Solo	DOI Card Expiration Date: 4/30/21

Participant(s)

Flight Crewmember 1:	DOI Card Required? No If Yes, Expiration Date:	Role: Visual Observer

Communication Plan, Flight Following and Emergency Plan		
CONTACT LIST (update on day of project as needed)		
Project Manager: Bob Progulske	Phone: 772-469-4299	E-mail: Donald_Progulske@fws.gov
UAS Remote Pilot in Command: Scott Bishaw	*Phone:* 239-595-9143	*E-mail:* scott_bishaw@fws.gov
UAS Flight Pilots: Layne Bolen Jeff Howe	*Phone:* 772-469-4332 772-469-4283	*E-mail:* *Layne_Bolen@fws.gov;* *Jeffrey_Howe@fws.gov*
Regional Aviation Manager: Steve Earsom	*Phone:* 301.980.8711	*E-mail:* Stephen_earsom@fws.gov
Air Route Traffic Control Center: Miami	*Phone:* (305) 716-1500	

RADIO FREQUENCIES (as applicable)		
Miami Homestead General Aviation (X51)	CTAF/Unicom: 122.8 Miami App/Dep: 125.5 Wx ASOS 305-247-2791	Airport Manager: David Gonzalez 305-247-4883
Homestead Air Reserve Base (KHST)	CTAF/UNICOM: 133.45	Airport Manager:
Miami Executive Airport (KTMB)	CTAF/Tower: 118.9 Miami App/Dep: 125.5	Airport Manager: Jonathan Spicer 305-869-1702
Miami ART-CC	App Final: 133.050; App South:120.500	Phone: (305) 716-1500

Flight Following

Line of sight flight following will be utilized by the remote pilot and visual observers. UAS operations will be coordinated with Dispatch, or appropriate authority prior to launch and when completed.

Emergency plan and other safety considerations

A first aid kit, fire extinguisher, and aviation radio will be available on site. For any emergency to life or property, DIAL 911. Any medical evacuation will be coordinated through the local emergency services. The nearest major medical facility is Homestead Hospital/Baptist Hospital South Florida. 975 Baptist Way, Homestead, FL 33033 (786-243-8000).

Prior to launching aircraft, as part of the Preflight Checklist, the Pilot in Command will ensure that the UAS is programmed to return to launch site and AUTOLAND if there is a loss of link between the controller and the aircraft. The altitude of the return flight will be programmed to be higher than the tallest obstacle in the area of operations.

If there is a loss of GPS signal during operations, the Pilot in Command will assume manual flight control and land the aircraft as soon as possible, or return the aircraft to "Fly" mode if GPS signal lock is reestablished.

If loss of link with loss of GPS occurs for more than 3 minutes, Miami ARTCC Air Route Traffic Control Center (ARTCC), (305) 716-1500, will be notified with the last location, heading, altitude, and battery time remaining of the UAS.

The UAS flight crew and participants will conduct a mission and safety briefing at the beginning of each operational period, and a debrief at the end of operations.

The UAS flight crew will adhere to DOI flight time and duty day policy.

Accidents involving major injuries due to aircraft, major damage to aircraft, or fly-aways, will be reported by calling the 24-hour Aircraft Accident Reporting Hot-line at 1-888-4MISHAP (1-888-464-7427).

Any condition, observation, act, maintenance problem, or circumstance with personnel or the aircraft that has the potential to cause an aviation-related mishap will be reported via the SAFECOM system.

Aerial Hazard Analysis
Since all flights will be conducted within line of sight, the pilot, and/or the visual observers, will identify the immediate aerial hazards once on location and prior to the first flight, as part of the safety briefing. A sectional chart is located on page 4.

Protective Clothing and Equipment
UAS crew members will utilize PPE required by their crew position. Personnel should be prepared for field conditions (heat stress, biting insects, inclement weather, intense sun, and dehydration).

Weight & Balance / Load Calculations
UAS will only carry payloads that have been approved by OAS, which already meet weight and balance specifications.

Risk Assessment/SMS

Risk Assessment Matrix

	Severity			
Likelihood	Negligible	Marginal	Critical	Catastrophic
Frequent				
Probable				*High 4*
Occasional			*Serious 3*	
Remote		*Medium 2*		
Improbable	*Low 1*			

Appropriate Management Level for Risk Decisions

Risk Level	Fire	Project
High	Incident Commander or Operations Sections Chief/designee	Regional Director
Serious	Incident Commander or Operations Sections Chief/designee	Assistant Regional Director
Medium	Air Operations Branch Director/designee	Project Leader
Low	UAS Remote Pilot	1st Line Supervisor with M3 Training

Severity Scale Definitions

Catastrophic	Mishap results in fatalities
Critical	Severe injury or greater than $500 damage to property/UAS
Marginal	Minor injury or less than $500 damage to property/UAS
Negligible	No injuries/UAS damage

Likelihood Scale Definitions

Frequent	Could occur often during the life of the PASP.
Probable	Could occur several times.
Occasional	Could occur once or twice.
Remote	Unlikely to occur, but possible.
Improbable	So unlikely, it can be assumed it will not occur.

Assess the risks involved with the proposed operation. Use additional sheets if necessary.

Describe the Hazard:	**Pre-Mitigation hazards rate out as:**		
	Likelihood	**Severity**	**Risk Level**
1. Collision with another aircraft – Crop dusting and agricultural helicopter in the area. Glider, ultralights, and parachute activities occur out of nearest airport: Miami Homestead General (X51): approximately 8 statute miles to the northeast. Alert Area: Concentrated flight training located approximately 5 statute miles to the NW.	Remote	Catastrophic	Serious – 3
2. Collision with personnel or vehicles – Occasional use of conservation access roads by private citizens on dune buggies.	Occasional	Critical	Serious – 3
3. Collision with a fixed aerial hazard	Occasional	Critical	Serious – 3
4. Aircraft flyaway (loss of control)	Remote	Critical	Medium -2
5. Aircraft loss of link with ground control station	Probable	Negligible	Medium -2
6. Injury caused by spinning propellers	Occasional	Critical	Serious – 3
7. Operations in adverse weather (wind, thunderstorms, etc.)	Occasional	Critical	Serious – 3
8. Battery fire	Occasional	Critical	Serious – 3
9. Collision with birds.	Remote	Marginal	Medium -2

Pre-Mitigation Overall Rating: Serious - 3

Example:

Mitigations:	Post Mitigation Hazard Assessment		
	Likelihood	Severity	Risk Level
1. The remote pilot will continuously scan the area for air traffic and other hazards to aviation and use a visual observer, when possible. The remote pilot will file a NOTAM 24 hours in advance of flight, when possible. The remote pilot will give way to manned aircraft at all times. The remote pilot will monitor general aviation radio channel.	Improbable	Catastrophic	Medium – 2
2. The remote pilot will conduct a pre-flight briefing, which will include flight patterns and safe observation/viewing areas. The remote pilot will not fly the UAS over personnel or vehicles not involved in the operation.	Remote	Critical	Medium – 2
3. Remote pilot will conduct a survey of operations area prior to operations, and use visual observers when possible.	Improbable	Negligible	Low – 1
4. Aircraft, personnel and ATC having jurisdiction over the airspace will be notified with the last location, heading, speed and approximate battery/time remaining of the UAS. Crew actions to recover UAS will also be relayed.	Remote	Negligible	Low – 1
5. UAS will be programmed to return to launch site and land.	Occasional	Negligible	Low – 1
6. Preflight briefing will include safety precautions when working around UAS with motors running.	Improbable	Critical	Low – 1
7. Remote pilot will obtain a current forecast and ensure the aircraft is flown within approved parameters. The crew will monitor weather conditions periodically during flights.	Occasional	Negligible	Low – 1
8. Batteries will be stored in accordance with safe handling procedures. Appropriate extinguishing procedures will be briefed.	Remote	Critical	Medium – 2
9. If a bird is encountered attempting to come in contact with the sUAS, the pilot shall land as soon as practical in order to prevent injury to the animal or aircraft.	Improbable	Negligible	Low – 1

Post-Mitigation Overall Rating: Medium – 2

The Airborne Hunting Act prohibits, among other things, using an aircraft to harass any bird, fish or other animal (16 U.S.C. 742j-1(a)). Exceptions to this prohibition (50 CFR 19.12) are available if the aircraft is operated to administer or protect or aid in the administration or protection of land, water, wildlife, livestock, domesticated animals, human life or crops. To meet the exception, the aircraft operator must (1) have a Federal permit, (2) have a State permit, or (3) be acting within the scope of his or her official duties as a Federal or State employee or authorized agent thereof (16 USC 742j-1(b)(1). This Project Aviation Safety Plan serves as the appropriate documentation authorizing the named operators to conduct flights as described herein.

Project Plan Review and Approval Signatures

Prepared by:

Layne Bolen March 24, 2019

Layne Bolen
FWS Endangered Species Biologist

Reviewed by:

SCOTT BISHAW Digitally signed by SCOTT BISHAW Date: 2019.05.24 12:45:52 -04'00'

Scott Bishaw
UAS Program Coordinator

Approved by:

DONALD PROGULSKE Digitally signed by DONALD PROGULSKE Date: 2019.05.29 13:30:15 -04'00'

Bob Progulske
Field Supervisor SFESO

UAS OPERATION GO/NO-GO CHECKLIST

*The purpose of this checklist is to provide the individuals participating in an UAS operation a systematic method to determine if all known factors are evaluated prior to flight. If any item listed on this checklist is checked in the NO-GO block, the air operations **will come to a halt** until that factor is changed to a GO and initialed off by the evaluator. Additional lines are available for specific factors that the evaluator determines are important that could create a NO-GO situation.*

Project name:

		GO	NO-GO	N/A
1.	PASP is current, approved, and signed at appropriate level, or air operation is under another approved authority (IFUAS Ops Guide).			
2.	Pilot in command (PIC), individual roles and responsibilities identified to all participants.			
3.	Pilot and aircraft approved for the type of mission, and card date is current.			
4.	All participants reviewed and understand the PASP.			
5.	All participants briefed on the mission and all known hazards (air and ground).			
6.	All participants have Personal Protective Equipment required for the specific field conditions.			
7.	Sectional and/or hazard maps reviewed prior to mission.			
8.	Authorization to fly in the specified location.			
9.	If operating in Restricted Airspace, controlling authority notified prior to launching UAS.			
10.	Adequate take-off and landing areas identified and or improved to minimum standards.			
11.	Pilot flight and duty times are not compromised.			
12.	Weather forecast is within manufacturers limitations. (wind, rain, visibility)			
13.	NOTAM filed via 1800wxbrief.com. (if applicable)			
14.	Dispatch notified prior to first flight. (if applicable)			

Checklist Evaluator Name/Signature: Date:

Daily UAS Safety Briefing

Briefing Leader:______________________________Date:__________________

Discussion Items:

__A. Hazard Analysis (as outlined in plan)

__B. Safety Air Ops (Ground)

__C. Safety Air Ops (Flight)

__D. Military Training Routes/Restricted Airspace Deconflicted

__E. Flight Following (Dispatch notified if applicable)

__F. Frequencies/Phone Numbers

__G. Lost Link Procedures

__H. Emergency Response Plan

__I. Authorities

__J. Weather Considerations

__K. Review applicable Risk Assessments

__L. NOTAM on file (if applicable)

__M. Other (identify)

APPENDIX 5. COLOR CLASSIFICATION AND PIXEL VALUES FOR UNSUPERVISED IMAGE CLASSIFICATIONS OF UAS PR FLIGHT SURVEYS

Unit 2; February and June 2019.

A. Flight Surveys

Unit 2 February 16, 2109		
Unique Color Classification	**Value (Calculated pixel count) ***	**Basic Color Group**
Burnt canopy	24,762,108	Brown
Vegetation	23,264,937	Light green
Burnt canopy	19,550,273	Maroon
Ground cover, limestone	19,502,698	Tan
Vegetation	17,426,200	Green
Limestone	13,201,745	White
Burnt canopy	12,935,600	Burnt orange
Burnt vegetation, ground	11,818,503	Black
Burnt vegetation, ground	7,353,579	Dark gray
Burnt vegetation, ground	5,971,324	Light gray

Unit 2 June 8, 2019		
Unique Color Classification**	**Value (Calculated pixel count) ***	**Basic Color Group**
Vegetation	69,239,638	Green
Shadow	63,106,096	Black
Vegetation	23,536,159	Olive green
Redland soil/pine needles/grasses	23,513,400	Mauve
Limestone	19,368,207	White

LAQIs Unit 2 WPT 35 July 2019; February 2020.

B. LAQIs

LAQI WPT 35 July 6, 2019**		
Unique Color Classification	**Value (Calculated pixel count) ***	**Basic Color Group**
Dead twigs, sticks, bark	4,258,270	Gray
Soil/shadow	3,462,830	Dark Brown
Shadow	2,519,236	Black
Old leaves/vegetation	1,681,439	Tan
Sticks/shadow	1,638,664	Light gray
Shrub vegetation	1,383,042	Dark green
Limestone	836,056	White
Ground vegetation	769,810	Green
Bark, pine needles	723,327	Brown
Soil	720,523	Light brown
Petunia bloom	594,498	Lavender
Pine needles	512,738	Mauve
Grasses	501,901	Light green
Palm vegetation	190,949	Green-blue
Lantana bloom	168,573	Yellow

LAQI WPT 35 February 22, 2020**		
Unique Color Classification	**Value (Calculated pixel count) ***	**Basic Color Group**
Pine needles	3,192,766	Tan
Shadow	2,878,296	Black
Limestone, shadow	2,225,298	Light gray
Shadow, bark, branches	1,977,187	Dark Gray
Branches, pine needles	1,856,934	Gray
Ground vegetation	1,497,479	Light green
Grasses, vegetation	1,368,600	Light green-blue
Shrub, palmetto	1,353,310	Dark green
Soil, tree bark	1,192,879	Brown
Limestone	838,000	White
Ground vegetation	799,495	Olive green
Shrub, palmetto	459,801	Green
Grasses	321,811	Bright green

Unit 2West LAQI 1; February 2020.

LAQI 1(Overgrown Shrub) Unit 2West February 22, 2020**		
Unique Color Classification	**Value (Calculated pixel count) ***	**Basic Color Group**
Dead vegetation	7,578,483	Tan
Live vegetation	5,519,104	Green
Shadow	3,010,711	Black
Live vegetation	1,822,614	Light green
Dead palm fronds	1,245,182	White
Pine needles/dead vegetation	785,762	Brown

* Ordered from High to Low Pixel Value.
**LAQI at 3.4 m (11 ft) altitude.

APPENDIX 6. SUPERVISED IMAGE CLASSIFICATION TRAINING SAMPLE STATISTICAL RESULTS FOR UNIT 2, FEBRUARY 16, 2019 AND FEBRUARY 19, 2020 UAS ORTHOMOSAIC IMAGES

NWells_SuperClassStats_Unit2_16Feb19

Canopy vegetation

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	18.00	64.00	6.00	255.00
Maximum	249.00	253.00	216.00	255.00
Mean	136.37	170.30	103.87	255.00
Std.dev	40.78	33.47	29.66	0.00
Covariance				
Band_1	1663.18	1306.89	1065.68	0.00
Band_2	1306.89	1120.43	859.05	0.00
Band_3	1065.68	859.05	879.78	0. 00
Band_4	0.00	0.00	0.00	0.00

limestone

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	124.00	121.00	104.00	255.00
Maximum	255.00	255.00	254.00	255.00
Mean	224.94	223.34	211.18	255.00
Std.dev	22.13	23.13	24.64	0.00
Covariance				
Band_1	489.56	499.65	514.74	0.00
Band_2	499.65	534.93	552.93	0.00
Band_3	514.74	552.93	606.89	0.00
Band_4	0.00	0.00	0.00	0.00

Charcoal soil

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	90.00	74.00	71.00	255.00
Maximum	184.00	159.00	152.00	255.00
Mean	130.39	123.78	119.55	255.00
Std.dev	16.23	12.61	10.85	0.00

Covariance				
Band_1	263.30	181.96	138.66	0.00
Band_2	181.96	159.01	128.53	0.00
Band_3	138.66	128.53	117.65	0.00
Band_4	0.00	0.00	0.00	0.00

Burnt canopy

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	80.00	34.00	26.00	255.00
Maximum	254.00	235.00	224.00	255.00
Mean	203.62	156.15	122.22	255.00
Std.dev	27.76	29.85	30.09	0.00
Covariance				
Band_1	770.58	780.28	693.02	0.00
Band_2	780.28	890.87	846.54	0.00
Band_3	693.02	846.54	905.42	0.00
Band_4	0.00	0.00	0.00	0.00

Burnt ground

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	94.00	45.00	31.00	255.00
Maximum	254.00	240.00	228.00	255.00
Mean	182.78	135.66	109.95	255.00
Std.dev	22.80	23.81	23.47	0.00
Covariance				
Band_1	520.04	505.62	458.98	0.00
Band_2	505.62	566.77	534.72	0.00
Band_3	458.98	534.72	551.04	0.00
Band_4	0.00	0.00	0.00	0.00

NWells_SuperClass_19Feb20

Grass

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	17.00	20.00	14.00	255.00
Maximum	167.00	157.00	146.00	255.00
Mean	72.52	64.47	45.67	255.00
Std.dev	26.88	22.09	16.19	0.00
Covariance				
Band_1	722.73	579.50	414.09	0.00
Band_2	579.50	487.75	343.79	0.00

Band_3	414.09	343.79	262.01	0.00
Band_4	0.00	0.00	0.00	0.00

Pine Canopy

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	5.00	29.00	1.00	255.00
Maximum	209.00	223.00	190.00	255.00
Mean	80.28	105.44	50.09	255.00
Std.dev	33.73	32.33	22.10	0.00

Covariance				
Band_1	1137.91	1075.94	654.50	0.00
Band_2	1075.94	1045.47	627.12	0.00
Band_3	654.50	627.12	488.47	0.00
Band_4	0.00	0.00	0.00	0.00

Limestone

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	42.00	43.00	44.00	255.00
Maximum	255.00	255.00	254.00	255.00
Mean	189.22	185.58	182.67	255.00
Std.dev	41.92	40.58	39.47	0.00
Covariance				
Band_1	1757.54	1681.54	1600.39	0.00
Band_2	1681.54	1646.56	1574.91	0.00
Band_3	1600.39	1574.91	1558.10	0.00
Band_4	0.00	0.00	0.00	0.00

Pine ground cover

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	25.00	13.00	10.00	255.00
Maximum	190.00	151.00	141.00	255.00
Mean	86.52	67.28	60.15	255.00
Std.dev	41.88	31.94	26.33	0.00
Covariance				
Band_1	1753.64	1311.69	1049.69	0.00
Band_2	1311.69	1020.39	826.21	0.00
Band_3	1049.69	826.21	693.32	0.00
Band_4	0.00	0.00	0.00	0.00

Palmetto

Statistics	Band_1	Band_2	Band_3	Band_4

Minimum	4.00	22.00	0.00	255.00
Maximum	233.00	253.00	232.00	255.00
Mean	71.06	92.23	67.14	255.00
Std.dev	33.65	31.92	32.49	0.00
Covariance				
Band_1	1132.40	1049.24	1018.76	0.00
Band_2	1049.24	1018.78	960.87	0.00
Band_3	1018.76	960.87	1055.39	0.00
Band_4	0.00	0.00	0.00	0.00

Shrub

Statistics	Band_1	Band_2	Band_3	Band_4
Minimum	4.00	14.00	0.00	255.00
Maximum	239.00	250.00	223.00	255.00
Mean	79.21	96.68	49.82	255.00
Std.dev	34.85	34.57	28.54	0.00
Covariance				
Band_1	1214.51	1175.77	910.82	0.00
Band_2	1175.77	1195.27	888.80	0.00
Band_3	910.82	888.80	814.50	0.00
Band_4	0.00	0.00	0.00	0.00

APPENDIX 7. EXAMPLE IN-FIELD QUADRAT FIELD ASSESSMENTS SPREADSHEET

Date	10/05/19	11/02/19	10/05/19	11/02/19	10/05/19	11/02/19	10/05/19	11/02/19	10/05/19	11/02/19	10/05/19	11/02/19	10/05/19	11/02/19
	34		35		41		42		43		44		47	
	Passiflora suberosa		Wetland petunia		butterfly pea		limestone area		white button		thistle C. horrigulum		C. rhododendron	
Ground Cover Type														
Pine tree (s)											5	5	5	
Limestone	40	10	10		5			40	5		55	60	55	10
Limestone/mix with pine needles (needles/with visible limestone)		50		5			30	10	50	40		10	10	50
Pine needles			60	65		3			10		15			
Grasses (make note dead vegetation on grasses and shrubs but not loose on ground)	10	20	10		80	90	40	25	15	40		5	10	
Herbaceous ground cover (forbs)	25 prevalent deltoids	10		20	15	5	10 - 20		20	20	5	10	10	10
Mixes of grasses and plants (forbs)														
Palmettos		5	5				10 - 20				5			5
Ferns	5										5			
Shrubs (woody)	20	5						25			10	10		10
Dead logs, branches			15	10		2								
Burnt ground (charcoal)														
Burn pine needles														
Burned logs, branches														

APPENDIX 8. PHOTOGRAPHS OF PINE ROCKLAND SPECIES, NAVY WELLS PINELAND PRESERVE, TAKEN BETWEEN JANUARY 11, 2019 AND FEBRUARY 22, 2020

L. Bolen

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