Low Power Wireless Networks in Vineyards

Allison Renehan
Systems Engineering
University of Virginia
Charlottesville, United States
apr7mc@virginia.edu

Bryan Rombach
Computer Engineering
University of Virginia
Charlottesville, United States
bmr3ud@virginia.edu

Anna Haikl
Systems Engineering
University of Virginia
Charlottesville, United States
ah8wt@virginia.edu

Corey Nolan
Systems Engineering
University of Virginia
Charlottesville, United States
cbn7gh@virginia.edu

William Lupton
Systems Engineering
University of Virginia
Charlottesville, United States
wbl5kg @virginia.edu

Eric Timmons
Systems Engineering
University of Virginia
Charlottesville, United States
emt7th@virginia.edu

Reid Bailey
Systems Engineering
University of Virginia
Charlottesville, United States
rrbailey@virginia.edu

***Abstract*— The focus of this work is developing an effective and cost-efficient monitoring system that collects spatially-granular data within a vineyard. Many vineyard managers currently rely on limited data paired with past experiences to make key decisions pertaining to frost prediction, pest and disease prediction, and irrigation optimization. Considering that soil conditions and microclimates vary significantly within a single vineyard, this lack of data prevents them from precisely managing their vines.**

By engaging stakeholders in iterative prototype development, we identified key design features of a low-cost, high-density sensor network for vineyards. Functionally, an ideal system 1) uses Long Range (LoRa) wireless communication technology; and 2) places temperature, humidity, soil moisture, and light intensity sensors in relevant areas throughout the vineyard. Additionally, by engaging with industry competitors, we learned that the market lacks low-cost, high-density sensor network implementations.

Using LoRa allows for a high density of sensors to be placed in every microclimate throughout a vineyard without relying on cellular coverage. The focus on temperature, humidity, soil moisture, and light intensity targets a low cost, minimally-viable set of metrics that can provide the necessary information for key models and decisions.

User input and site visits suggested that the system must endure harsh environmental conditions and relay timely, actionable data without disrupting fieldwork. To prevent damage and extend device lifetime, the sensor housing and connections need to be waterproof and durable. Further, vine growing methods are not standardized across the industry, meaning the product needs to be adaptable to different growing styles. Vineyard managers want a system that informs their decisions by providing data and the results of established prediction models. The research presented here shows that a system incorporating these features and minimizing costs will be valuable in vineyards while also being broadly applicable to a variety of other agricultural applications.

I. Introduction

Recent advances in Internet of Things (IoT) technology have allowed for connectivity and data collection where it was previously unavailable, such as in areas without access to power or an existing network. Low Power Wide Area Network (LPWAN) technologies allow for extended battery life, long range, and low-cost hardware. These advantages are best suited for applications which are:

- granular (i.e., a large number of sensors)
- low bit-rate (i.e. sending minimal data per second)
- regular, not real-time (i.e., where latency of a few seconds is not a concern)

Extracting environmental sensing data from semi-remote areas such as those found in agriculture is a promising use case. This work focuses on vineyards as a case study for agricultural use of LPWAN. In particular, key factors for using long range, low power technology to collect data in vineyards to better inform decisions are characterized.

Through studying LPWAN in vineyards, we can understand the scalability, need, and market adaptation for future agricultural applications. Grape vines are sensitive to differences in soil conditions and microclimates – small areas of vineyard, sometimes unique to the individual vine, that are differentiable by their environmental conditions – and are highly valuable. Current technology also lacks the ability to measure these differences cost-effectively. Thus, vineyard managers rely heavily on in-person observations and experience-based knowledge to make decisions.

This work investigates implications for the functionality, form, and user experience of LPWAN products. The investigation into functionality focuses on range and battery life. The investigation into form focuses on where the data will be collected, how the product will be placed in the vineyard, the appearance of the product, and how to overcome the harsh conditions it will be exposed to. Lastly, the investigation into the user experience focuses on what data is needed by whom, when, how, and in what format. Together, the specifications for an agricultural monitoring system that will address issues currently faced by vineyard managers are outlined.

II. Literature Review

Although the utilization of LPWAN technologies in vineyards is recent, the deployment of large-scale wireless sensor networks (WSN) in agricultural settings is a well-established topic of research. In 2004, Intel funded research into the needs and priorities of people working in vineyards to gain a better understanding of the potential for sensor networks in agriculture [1]. More specifically, this research touched on two major observations. 1) Developing a completely automated system that determines when to harvest would be nonideal because actions of this nature are a subjective and social decision based on incomplete information. 2) The interface design and implementation of human touchpoints in the sensor network infrastructure must take into account collaborative work environments and provide mediation between vineyard managers, owners, workers, and winemakers. This prior work demonstrates that the way work is done in vineyards—and other agricultural operations—has direct implications for designing and configuring sensor networks in these environments. Furthermore, the study determined that domain knowledge is required to design such a system [1].

While Intel's research has been pivotal in the refinement of functional requirements for vineyard sensor networks, other research from the early 2000s was focused more heavily on the improvement of technical performance. A. Cerpa et al. recognized that the vast majority of the biodiversity—and resulting biocomplexity—within an ecosystem exists at very small scales and is not readily observable with even the best airborne or satellite-based sensor [2]. As a result, the study aimed to address the technical challenges faced by existing wide area network systems, primarily focusing on power efficiency and signal processing of sensor nodes.

Although considerable research into WSNs was conducted during the early 2000s, the evolution of LPWAN protocols began in 2009 when French telecommunications company, SIGFOX, built the first LPWA network in France. This motivated other companies in the telecommunications space to develop their own products using this network [3].

Since then, the advancement of LPWAN protocols has motivated research across agricultural applications. Much of this research has utilized a new protocol known as LoRa—an emerging LPWAN technology that uses license-free radio-frequency bands to transmit small data packets over a long distance (~10 km) with minimal power consumption. For example, Intel researchers Beckwith and Tieble used LPWAN sensor networks to prove that WSNs can, in fact, provide actionable data in a variety of ways. Their research found that the collection and analysis of temperature data optimize vineyard managers' decisions for harvest, frost intervention techniques, and disease management optimization [5].

As LPWAN research continues to expand, there are a number of characteristics of existing LPWAN solutions lacking research. Ojha and Misra's survey of the state-of-the-art in WSNs and applicability to agricultural and farming applications found that research is lacking in the following areas [6]:

- Cost-effective solutions for low/middle-income countries
- Testing the scalability of the deployments
- Fault tolerance
- Energy management and energy harvesting
- Simplification of the existing solutions

By combining both a technical and ethnographic perspective when assessing the potential of LPWAN in agriculture, this research aims to address these research gaps, particularly with a focus on finding a more cost-effective solution for vineyard monitoring.

III. Methods

To characterize the potential of LPWAN in vineyards, we researched the relevant technology, engaged stakeholders, and developed prototypes. Our process was highly iterative, with each iteration leading to deeper insights about the users, vineyards, and the capabilities of the technology.

Engaging stakeholders included site visits to vineyards, interviews and prototype demonstrations with vineyard managers, and interviews with representatives from companies with related products currently on the market. Site visits included five vineyards in Virginia and one in California: one less than 10 acres, four between 10 and 50 acres, and another greater than 50 acres. Of the nine vineyards managers and consultants interviewed, six were in Virginia, two were in California, and one was in Argentina. Product representatives from 25 companies were interviewed in person at the Unified Wine and Grape Symposium in February 2020, while 7 additional related products were researched through online materials. Prototyping centered on three interrelated facets of the final design: functionality, form, and user experience. Multiple rounds of these prototypes were shown to vineyard managers to gain user feedback.

IV. Vineyard Manager Interviews

A. *Vineyard Decisions*

The complexities and variability of conditions both above and below ground at vineyards are not captured by most current data collection methods. Above-ground data collection at vineyards is primarily done with on-site weather stations. Vineyards that are unable to afford weather stations instead use publicly available websites and online services to inform decisions. With limited site-specific data available, vineyard managers have to rely heavily on experience and in-person observations. Below-ground, the intensity of data collection depends on the demand for irrigation water. In California, where the demand is high, water authorities measure soil moisture throughout vineyards as part of water conservation programs. In Virginia, where rainwater is sufficient most years, soil moisture is not routinely measured.

The vineyard managers interviewed desired more granular data to allow for high precision management of different microclimates and soil types located throughout a vineyard [7,8]. Certain areas within the plant structure hold more valuable information than others. Specifically, each vine has a fruiting zone (Fig. 1) where grapes grow. Temperature, humidity, and light conditions in the fruiting zone directly impact the development of the fruit.

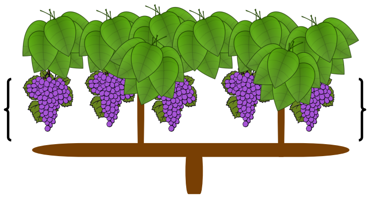

Fig. 1. Vine sketch (with fruiting zone emphasis added)

Vineyard managers and consultants value fruiting zone data because it allows them to comprehend the grapes' health in great detail. Weather stations don't measure the fruiting zone and it is cost-prohibitive to install multiple across a vineyard.

Emerging from our interviews were three major use cases for more precise data in vineyards: 1) disease and pest mitigation, 2) irrigation optimization, and 3) frost prevention. The data needed for these use cases are ambient temperature and humidity; fruiting zone temperature, humidity, and light levels; and soil moisture at multiple depths.

Pathogens and pests are universal across all climates and vineyard sizes. Vineyards spray various forms of fungicides and pesticides to reduce the risk of disease and pests, although species of disease and pest, frequency, and potency of sprays vary across climates and vineyards. Spraying is labor-intensive, costly, and diminishes grape quality, so vineyard managers are eager to minimize spraying. Currently, prediction models such as the one from the University of California at Davis (UC Davis) can be used to assess the risk of a variety of diseases and pests, allowing managers to make informed decisions. These models use combinations of ambient temperature, humidity, and light intensity measurements within the fruiting zone to calculate risk [9]. With fruiting zone data unavailable and conditions varying across a vineyard, vineyard managers instead make many spraying decisions based on the labor-intensive and imprecise visual inspection of vine conditions.

Vineyard managers located within climates that require supplemental watering (e.g., California and Argentina) need to regularly make crucial choices to minimize water usage. By assessing soil moisture (commonly read at varying soil depths), vineyards can move away from fixed watering schedules which invariably waste water. In places like California where water is a scarce resource, some grape-growing regions are outfitted with soil moisture sensors by local water authorities who send representatives on a weekly basis to record readings. These programs have led to drastic reductions in water usage. Such water monitoring and the associated benefits are not widespread in the industry; they are only common where water authorities subsidize the costs.

Since a single frost can destroy a large portion of grapes within a few hours, managers are constantly monitoring conditions to prevent such an event. By tracking incoming weather conditions through their own weather stations as well as publicly available data, vineyard managers determine if, when, and where to implement the appropriate prevention response. These prevention responses come in varying forms, but all are labor and cost-intensive. Thus, managers would like to ensure proper deployment to prevent grape loss. Yet, with limited localized weather data, vineyard managers are unable to accurately predict the risk of frost for their vineyard; minute differences in elevation, wind intensity, or moisture.

B. Vineyard Conditions

We also gained an understanding of the conditions in which the system would be implemented. In particular, there are a variety of vine trellis structures that are used in vineyards. Though there tend to be similarities within regions, each vineyard can offer unique combinations of wiring layouts and metal or wooden support posts. These differences in trellis configuration have an impact on the installation, and thus the success, of a vineyard monitoring system.

The system also needs to withstand the conditions found in vineyards—namely exposure to water, dirt, chemical spray, a wide temperature range, and agricultural machinery (including hand-powered tools such as pruning shears). Together, these conditions contribute to a harsh environment for a potential system with many technological aspects in need of protection.

A final consideration for system design is the limited cellular connectivity at vineyards. Since vineyards are often located in rural areas, cellular connection is not a guarantee. Additionally, varying topography within a vineyard makes reliable connection even more uncertain. Thus, a successful vineyard monitoring system can function without relying on cellular connectivity.

V. Existing Products and Services

Many of the findings from interviewing vineyards managers were reinforced by research into the current state of vineyard sensing products. At the Unified Wine & Vineyard Symposium, we spoke with twenty-five vendors of related products and services. The companies ranged from a startup, run by just a few people, to well-established international brands such as Davis Instruments. Each product had its own selling points, but wide-ranging insights emerged concerning high-density sensor installations.

Flexibility and expandability are common features, allowing the addition of a variety of sensors. A common connection standard, SDI-12 is used across the industry and sensor manufacturers produce universal plug-and-play sensors. The key sensors which were built into the majority of devices were humidity, temperature, and soil moisture. This is true of tailored devices by startups and standard packages by large companies.

LoRa is largely absent from the current market. Most companies are using either cellular connection or a proprietary 900 MHz band network. Only one company, a recently formed startup, uses LoRa. The companies using a non-LoRa 900 MHz technology had developed the technology in-house before LoRa became widely adopted. The one company using LoRa also had initially developed a proprietary protocol but switched when LoRa was found to be simpler, more power-efficient, and more reliable.

VI. Characteristics of an LPWAN Vineyard Data System

The main opportunity for LPWAN in vineyards is providing higher precision data, including from the fruiting zone, to inform pest and pathogen prevention, irrigation, and frost mitigation decisions. This precision is important due to the variability of microclimates and soil conditions within a single vineyard. Current systems on the market could collect such data but are limited to use as single-point weather stations by their high costs. The low cost, low power, and long range of LPWAN provide a market threat to products using other networking. To advance the realization of this potential, we iteratively developed multiple prototypes for the function, the form, and the user experience of an LPWAN vineyard data system. The findings from testing and user feedback are presented in the following three subsections.

A. Findings from Functional Prototyping

The challenge facing an agricultural monitoring system delivering relevant data is not the complexity of necessary sensors—most models are based primarily on a combination of temperature, humidity, and soil moisture. Rather, the difficulty is in gathering the data and maintaining the longevity of sensing nodes cost-effectively.

LoRa is an LPWAN technology well-suited to these constraints. LoRa refers to the physical layer enabling long range communication and is complemented by the LoRaWAN communication protocol and system architecture for the network. Similar to the well-known Wi-Fi protocol, LoRaWAN operates as a star architecture, in which nodes communicate directly with gateways. Distinctly, whereas a computer and a Wi-Fi router have a one-to-one relationship, LoRaWAN nodes are not associated with a specific gateway. Data transmitted by a node can be received by one or more gateways and is de-duplicated later.

In comparison to another popular Internet of Things topology, mesh networks, the star architecture has lower power consumption and software complexity because it does not require devices to remain awake to pass on messages from neighbors. Necessarily, this results in LoRaWAN's range being limited by the connection range between a node and gateway rather than by the distance to the nearest node which is connected to the network. As suggested by the Long Range name, however, this limitation is not overly restrictive.

The primary alternatives to LoRa among LPWAN technologies are cellular based: NB-IoT and CAT-M. These were considered initially but dismissed due to the lack of cellular connectivity in many vineyards, higher battery consumption, and the requirement for a data plan for each node. Although an agricultural system would not be transmitting large quantities of data, the subscription fees quickly become more expensive than the cost of a LoRaWAN gateway. Despite this, CAT-M or NB-IoT could be integrated to extend the versatility of the system by enabling a gateway to connect to cellular if a wired connection was not easily available in a vineyard.

LoRaWAN claims a range of approximately 10km, depending on a variety of factors. In preliminary testing at a Virginia vineyard with trees, rolling hills, and some wooden structures, a range of 0.75mi was achieved between a Things Network Uno and a Things Network gateway placed in a ground floor window. This range allows for coverage of approximately 1,000 contiguous acres and can likely be increased with better placement of the gateway and an improved node antenna.

Each LoRaWAN gateway can support hundreds of nodes within its range. This allows the system to accomplish one of its key advantages: incredible density. Sensing nodes can be distributed evenly, densely packed in area, or even vertically stacked to meet the needs of the system owner and provide detailed information for the heterogeneous areas of a vineyard.

With the addition of soil moisture sensing through the versatile SDI-12 protocol, irrigation can be managed more precisely by area and reports can be generated for governmental regulations on water usage. The same SDI-12 port could allow system owners to extend functionality in other ways by adding compatible sensors as needed.

LoRaWAN is among the lowest power LPWAN technologies. Reporting several times an hour, a node could last for a year or more on alkaline batteries. With rechargeable batteries and a small solar panel, a node would have an effectively unlimited lifespan without manual recharging or replacing batteries.

B. Findings from Form Prototyping

Form prototyping focused on the physical structure to contain the components that deliver functionality. Based on the findings from discussions with vineyard managers and site visits, the form of the device must be able to:

- house electrical components that sense and enable LoRa communication
- position electrical components appropriately
- temperature, humidity, and light sensors in the fruiting zone
- temperature and humidity sensors in the ambient environment
- moistures sensors at multiple soil depths
- communication antenna high above the vines
- protect the electrical components from the vineyard environment such as machinery and chemicals
- attach/mount on different vine-trellising approaches
- access power to supply to the electrical equipment

From those functional requirements, the following design requirements emerged. The device shall:

- measure at three different vertical locations:
- above the vines in the ambient environment
- within the fruiting zone
- in the soil at the base of the plant
- allow for customization to match needs
- not rely on a specific style of trellis structure
- not interfere with tending to the vines

Two alternative designs, the "Boxes Design" and the "Pole Design", were considered for embodying these requirements. Both of employ modular components for product customization

The Boxes Design (shown in Fig. 2) encapsulates each set of sensors at their specific vertical locations in their own protective box. The *soil moisture box* would be in the form of a stake inserted in the ground with the sensors at different depths. The *fruiting zone box* would house multiple sensors, with small slits on the side for the temperature and humidity sensors and a clear window for the light sensor. This box would clip to the overhead wire common to most vineyards, with adjustable straps to position it in the fruiting zone. The *ambient box* would be identical to the fruiting zone box but would require a post for the box to be strapped to. The modular boxes of the Boxes Design enable users to choose which of the three types of boxes they want to best match the monitoring needs of their terrain.

One variation of this design puts a LoRa chip and battery in every box (shown in Fig. 2). Another variation only puts a LoRa chip and battery in the centrally located fruiting zone box, with wires connecting the ambient and soil moisture boxes. The two variations of this design come with tradeoffs. While having a LoRa chip in each box allows the boxes to be placed in completely different locations within a vineyard, component costs would increase. Alternatively, connecting the boxes with wires introduces the possibility of the wires being damaged by machinery.

The Pole Design, shown in Fig. 2, consists of multiple sections that can be connected to form a single pole.

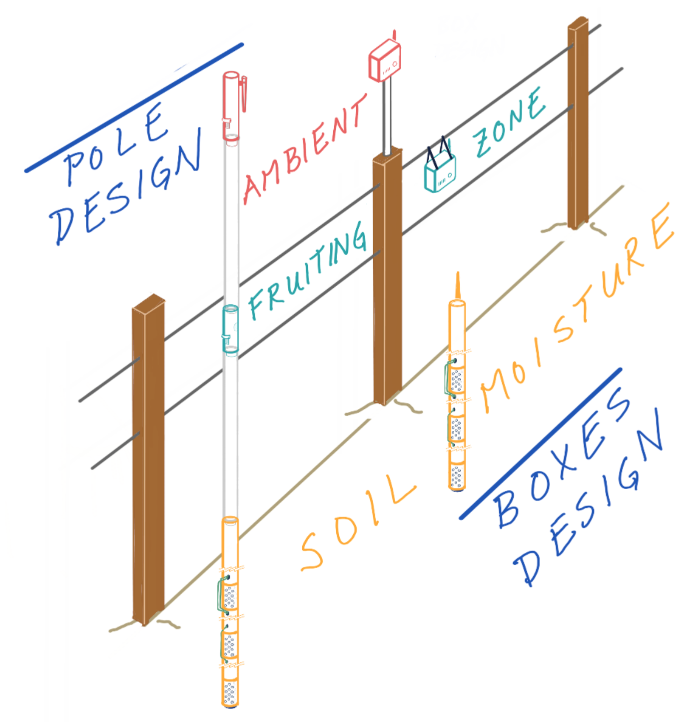

Fig. 2. Pole Design (left), Boxes Design (right)

The Pole Design enables a single LoRa chip and battery to be used for all three sensor locations while protecting the necessary wires within the pole itself. It is also free from any dependency on the trellis structure. Having all three sensor segments in the same unit, however, does remove some of the flexibility that is present in the Boxes Design.

Modularity of this design is accomplished with a standardized interface between pole sections. This modularity affords many advantages in customization, including the use of different length non-sensor sections (e.g., the ambient/communication segment could be 10 ft above the vines to improve communication range) and poles that are either soil moisture only or fruiting zone only. Preliminary discussions with vineyard managers have shown a preference for the more integrated Pole Design. They particularly noted the convenience of having only one housing to move (and avoid) when working in the vineyard.

C. *Findings from User Interface Prototyping*

We developed user interface mock-ups to facilitate meetings with and collect feedback from vineyard managers and owners. Through this feedback, the wireframed UI prototypes became iteratively more refined, informed, and inclusive of the needs of end-users. The user experience for a vineyard manager needs to provide current data in a form that relates to daily vineyard management decisions (e.g. Do I need to irrigate? Which plots? When? How much?) and store historical sensor data for year-to-year comparisons and summary reports.

For daily management decisions, vineyard managers were clear that they want data to inform their judgment. Vineyard managers' familiarity with their grapes and experience in the field provides them the expertise to form their own decisions. Since vineyard managers are frequently in the field, especially in the growing season, it is necessary to provide relevant information to the managers on the go. This is best implemented through accessibility on a mobile device. The mobile interface should provide the ability to inspect reports on frost, pests and diseases, and irrigation—composed of relevant sensor data—and enter new observational data.

In addition to the many decisions that vineyard managers make in the fields, they also make significant decisions regarding overall vineyard health and year-to-year continuity. Considering that these decisions require greater amounts of data and analysis, they are best facilitated through a desktop interface. Insight from vineyard managers showed that due to the considerable variability of environmental factors between growing seasons, they are also interested in comparing past results to the current season. In Virginia, vineyard managers identified that changes in temperature, soil moisture, humidity, and sun exposure distinctly affect the growth cycle of grapes, and storing historical data for year-to-year comparisons helps managers identify how weather affects important developments of their grapes. The historical data should include sensor data and also user-inputted data such as when, where, and for how long vines were irrigated. At a high level, the historical desktop UI design should provide the ability to compare weather and grape growth trends across years and access detailed summary reports.

We wireframed mobile and desktop interfaces to embody these requirements. The presentation of data for live, every day, active management in the fields is optimized for a mobile interface because it will be used in the field. The primary screens are grouped by decision and use-case with separate views for pests, disease, frost, and irrigation. A sample is shown in Fig. 3.

Of note:

- the most important information — a map view of the property coded with risk levels — is prominent
- the middle bar allows a user to navigate quickly to any of the four decision UIs
- the bottom half allows vineyard managers to add notes and key observations from the field

The presentation of historical data, optimized for a desktop UI, allows year-to-year comparisons of weather and grape growth. This data is accessed less frequently than data related to routine active management decisions and not while in the field. A sample is shown in Fig. 4.

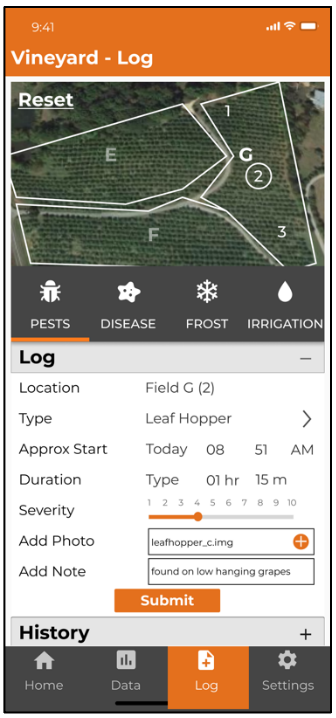

Fig. 3. Mobile - Pest Threat Log

Fig. 4. Desktop – Grape Growth Cycle History

In Fig. 4, the user sees an overview of important milestones in a grape's growth cycle for four years. This is linked to historical summary reports of sensor data to help users understand how weather variability affects grape growth year-to-year. For example, a user could identify bud break occurs earlier in warmer years, informing them that their grape will be exposed to pests, disease, and frost earlier in the year. A holistic, high-level understanding of this data will enhance strategic, year-to-year management of a vineyard.

VII. Conclusion

The advent of IoT technology with long range and low power capabilities enables more versatile connectivity and data than ever before. Vineyards are an ideal application for LPWAN protocols like LoRa to create effective and cost-efficient monitoring systems that optimize a vineyard manager's decisions by collecting more spatially-granular data than what was previously available. By using a high-density network of strategically-placed sensors in every microclimate throughout a vineyard, vineyard managers are able to access the metrics needed to accurately model their risk with respect to frost, pest and disease prediction, as well as irrigation optimization. While sensor systems for vineyards currently exist, high-density deployments are rare due to their high cost. LPWAN provides an opportunity to lower the cost and thereby make more spatially-granular data available. In addition to having demand within the grape-growing industry, this could have further implications throughout the agricultural industry.

References

[1] J. Burrell, T. Brooke, and R. Beckwith, "Vineyard Computing: Sensor Networks in Agricultural Production," Pervasive Computing, IEEE, vol. 3, pp. 38–45, Feb. 2004, doi: 10.1109/MPRV.2004.1269130.

[2] A. Cerpa et al., "Habitat monitoring," p. 19.

[3] "The Past, Present, & Future of LPWAN." https://www.link-labs.com/blog/past-present-future-lpwan (accessed Mar. 30, 2020).

[4] "(PDF) Unwired wine: Sensor networks in vineyards." https://www.researchgate.net/publication/4128507_Unwired_wine_Sensor_networks_in_vineyards (accessed Apr. 05, 2020).

[5] R. Beckwith, D. Teibel, and P. Bowen, "Unwired wine: Sensor networks in vineyards," presented at the Proceedings of IEEE Sensors, Nov. 2004, vol. 2, pp. 561–564 vol.2, doi: 10.1109/ICSENS.2004.1426227.

[6] "Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges - ScienceDirect." https://www.sciencedirect.com/science/article/pii/S0168169915002379 (accessed Mar. 30, 2020).

[7] C. King. "UVA Vineyard Research Project Visit". Personal Emails and Interview (2019, 2020).

[8] R. Corpora. "UVA Capstone Engineering Team Visit". Personal Emails and Interview (2019).

[9] University of California, "Grape Pest Management Guidelines," *Grape Pest Management Guidelines*. [Online]. Available: http://ipm.ucanr.edu/PMG/selectnewpest.grape