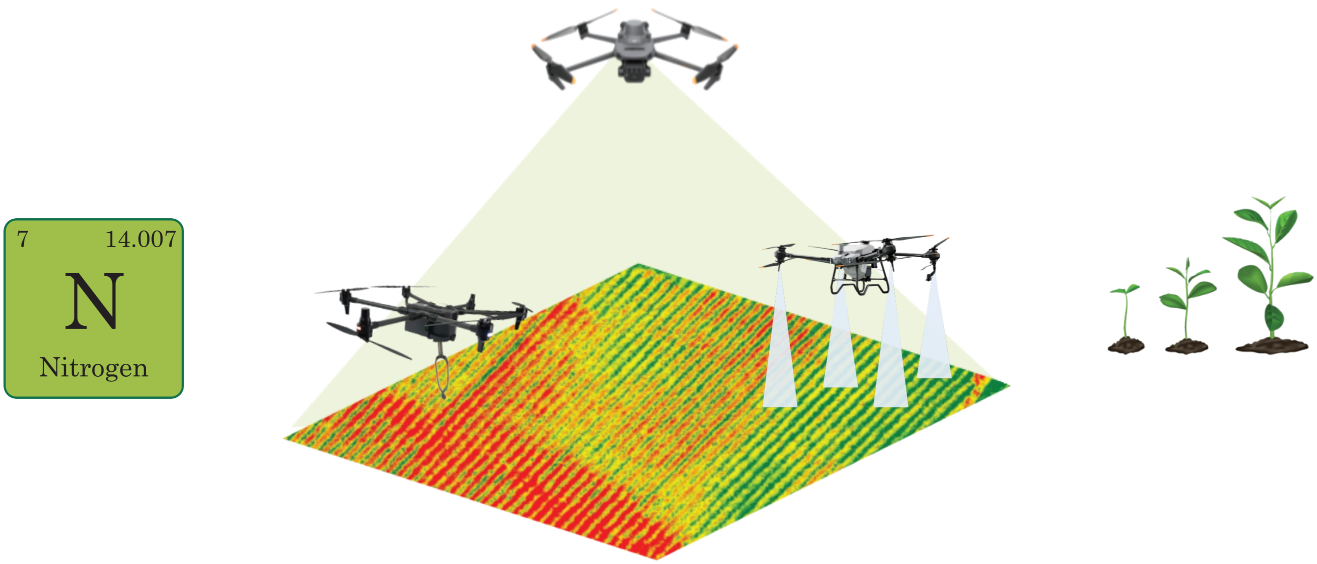
Boston University
College of Engineering, Department of Mechanical Engineering

PLAANT



Precision Land Assessment and Aerial Nitrogen Treatment

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PLAANT

Precision Land Assessment and Aerial Nitrogen Treatment

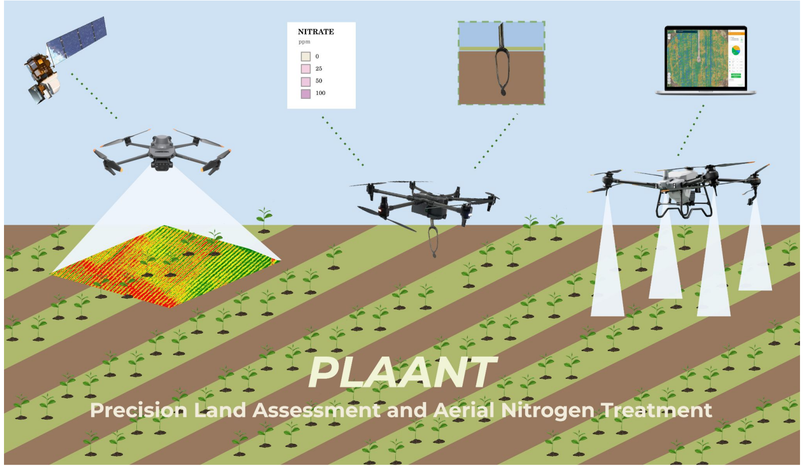
Project Summary:

Agricultural Area/Management Practice:
Enhanced Nutrient Management & Targeted Fertilizer Application

Use Case: Strategic detection and precise resolution of varying nitrogen landscape with corresponding automatic precise fertilizer response on large N-consuming, high-production farms.

Summary: Our solution seeks to improve lack of real-time understanding of nitrogen distribution, improving limited remote sensing practices with in-situ, automated soil sampling. The system then responds to this improved understanding with automated application of precisely targeted fertilizer, drastically improving production, profit, and environmental impact.

Project Image:



Team Composition:

<u>Boston University Engineering Capstone</u>

Jillian Martin – Senior, *B.S. Mechanical Engineering*

John Fitzgerald – Senior, *B.S. Mechanical Engineering*

Addison Chu – Senior, *B.S. Mechanical Engineering*

Charles Litynski – Senior, *B.S. Mechanical Engineering*

Ethan Jackson – Senior, *B.S. Mechanical Engineering*

We are mechanical engineers with expertise in environmental technologies, aerospace, and automation engineering. As Boston University trained Societal Engineers®, we seek to engineer environmentally and socially impactful solutions. We take these motivations into our work on *PLAANT.*

Proposed Deployment Timeline:

<u>2025 – 2026</u> → Rapid research and development (R&D), grant application (e.g. NIFA AFRI), program coordination (e.g. NRCS TSP), outreach to key land-grant university extensions.

<u>2027 – 2029</u> → Advanced testing and early commercialization, piloting in identified primary locations in IL, IA, IN, NE. Solution adjustment as needed.

<u>2030</u> → Full U.S. commercial launch, focussed on outward growth from the corn belt region to other high PA adoption states.

<u>2032 – 2033</u> → International R&D, coordinating with international organizations (FAO and IFAD) and location-specific resources.

<u>2034</u> → Targeted widespread U.S. commercialization. Pilot testing in developed PA regions globally.

<u>2035</u> → Initial global deployment.

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List of Abbreviations

Abbreviation	**Definition**
ARS	Agricultural Research Service, *agency of the USDA*
BVLOS	Beyond Visual Line of Sight
CES	Cooperative Extension System, *program of USDA NIFA*
CSP	Conservation Stewardship Program, *program of USDA NRCS*
EQIP	Environmental Quality Incentives Program
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAO	Food and Agriculture Organization of the United Nations
GNSS	Global Navigation Satellite System
GHG	Greenhouse Gas
GIS	Geographic Information System
GPS	Global Positioning System
IFAD	International Fund for Agricultural Development
N, N-	Nitrogen, Nitrogen-
N_2O	Nitrous Oxide
NDRE	Normalized Difference Red Edge
NDVI	Normalized Difference Vegetation Index
NIFA	National Institute of Food and Agriculture, *agency of USDA*
NRCS	National Resource Conservation Service, *agency of USDA*
NUE	Nitrogen Use Efficiency
PA	Precision Agriculture
ROI	Return On Investment
RTD&E	Research, Testing, Development, and Evaluation
RTK	Real-Time Kinematics
TSP	Technical Service Provider, *program of USDA NRCS*
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
USDA	United States Department of Agriculture
VRT	Variable-Rate Technology

Abstract

Targeted application of fertilizers and protectants remains a critical agricultural challenge to crop yield, environmental impact, and agro-economics. Applied nitrogen fuels global agriculture, but the dynamic nature of nitrogen nutrient cycling drives inefficiencies in contemporary fertilization, with up to 50% of applied nitrogen lost through emissions, runoff, and leaching—inducing excessive costs and environmental degradation. As the agricultural industry faces the challenge of sustaining the growing population while navigating resource scarcity and climate pressures, the demand for more efficient, sustainable fertilization methods is clear.

To address this, the team proposes *PLAANT*: *Precision Land Analysis and Aerial Nitrogen Treatment. PLAANT* is designed for optimal use on mid-to-large-scale, high N-consuming, high-output cereal row crop farms, with modularity to scale to other use cases. *PLAANT* comprises three integrated, unmanned aerial vehicle (UAV)-powered stages: remote nitrogen sensing with multispectral UAVs and satellite imagery, soil sampling UAVs, and sprayer UAVs for the application of targeted fertilizer. The system determines Nitrogen Use Efficiency (NUE) by gathering real-time crop health and nitrogen variability data from multispectral surveyance and physical soil analysis. Fertilizer sprayer drones then respond to apply nitrogen at variable rates based on information from the precise NUE model. These components work as a seamless, data-driven system; synthesizing surveyance, soil analysis, and fertilizer application to enhance resource efficiency, reduce nitrogen waste, and improve crop yields. *PLAANT* will be deployed strategically, targeting broad U.S. adoption and early international adoption by 2035. This is supported along the way by agricultural incentives, stakeholder investment, and facilitatory programs. Key design improvements include a detailed cost, value, and business analysis; adoption rate projections; refined system modularity and interoperability; drone sizing analysis; improved fertilizer application; and further consideration of potential risks. Environmental impact modeling substantiates projected improvements, while a revised deployment timeline targets broad U.S. implementation by 2034 and initial international launch by 2035. Late-stage validation of the design by NASA Acres researcher Prof. Wang and Precision Agriculture expert Prof. Khosla corroborated the changes made. *PLAANT* represents the future of agricultural sustainability—advancing food security, reducing environmental harm, and empowering farmers with a cost-effective, high-precision solution to meet the evolving demands of modern agriculture.

Acknowledgments

The conceptualization, development, and validation of this system would not have been possible without the guidance and support of several individuals in the academic, scientific, and government sectors. The team would like to extend our gratitude to Boston University **Professor James Geiger**, for providing indispensable advice as the team's faculty advisor throughout the life cycle of this project. The team would also like to thank Boston University **Professors Mark Friedl**, **Michael Dietze**, and **Kenn Sebesta** for extending their expertise and insights on remote sensing for crop management and forecasting, data analysis and physical/remote soil sampling techniques, and drone specification and operation, respectively. Outside of the team's home university, the team extends its gratitude to **Professor Hemendra Kumar** of the University of Maryland and **Professor Xia Zhu-Barker** of the University of Wisconsin-Madison, for their knowledge on UAV-driven precision agriculture and fertilizer NUE, respectively. We are deeply thankful to **Professor Raj Khosla**, of Kansas State University, whose continued support and foundational work in precision agriculture and expertise in addressing the spatiotemporal heterogeneity of agro-ecosystems, along with the practical implementation of PA technology, proved invaluable to our system's development. We would also like to acknowledge **Professor Sheng Wang** of the University of Illinois Urbana-Champaign, a member of the NASA Acres project *Remote Sensing and Agroecosystem Modeling to Support Resource-Efficient Nitrogen Management in the Midwest*, for his insight into the operation of a cross-scale nitrogen management system, including data assimilation needs for precision agriculture and soil sampling. Lastly, we would like to thank **Mr. Miguel Oliveras**, USDA NRCS TSP Certifier for the USDA Central U.S. region, for his guidance on integrating our system into practical use within the target market and navigating relevant government programs. The team is deeply grateful for the generosity and support of all these individuals, whose time and insights were instrumental to our progress.

I. Situational Assessment

A. Down-Selection

The eight competition-suggested problem areas were assessed through six metrics: cost, scope, environmental impact, technological development, opportunity for improvement, and future trends. The resultant decision matrix revealed *Weather Prediction Update Accuracy and Frequency* and *Targeted Application of Fertilizer and Protectants* as the highest impact areas [*Table A.1*]. The area of *Targeted Application of Fertilizer and Protectants* offers the opportunity to directly address the environmental issue of overapplication at its source, whereas improvement of weather prediction is a reactive response to a drastically changing climate rather than a proactive solution to mitigate underlying drivers; to this end, *Targeted Application of Fertilizer and Protectants* was chosen as the final focus.

B. Targeted Application of Fertilizer and Protectants

The agricultural industry is at a critical point in the modern age, tasked with the challenge of meeting the production demands of a growing world population, projected to reach 10 billion by 2061.[1] This challenge is compounded by resource scarcity of arable land, water, and energy, while the increasing impacts of climate change further heighten the need for sustainability. Modern agriculture disruptions such as COVID-19, extreme weather events, conflicts, and inflation have tightened nutritional access, such that 2 billion people currently face moderate to severe food insecurity.[2] Even in the most developed nations, the current agricultural system presents challenges as a leading driver of the climate crisis, draining water resources, polluting surrounding areas, and directly contributing over 10% to global greenhouse gas (GHG) emissions.[3] To meet increasing demands and environmental concerns, the agriculture industry must substantially increase efficiency. Fertilizers and protectants are essential for supporting crop yields by providing supplemental nutrients and preventing crop loss from pests and diseases. However, traditional fertilization methods apply these resources uniformly, ignoring field-specific variations in nutrient demand. Targeted application addresses this, precisely distributing chemicals based on varied real-time needs to reduce waste and adverse impact. Precision agriculture (PA) uses technology and remote sensing to optimize crop management, enhance yield, and apply resources—like fertilizer—more efficiently. Variable-rate technology (VRT) fertilization using global navigation satellite system (GNSS) guided ground vehicles has been available for decades, yet less than half of growers utilize the technology due to perceived barriers in cost, complexity, and data interpretation.[4-5] Future demands highlight the importance of advancing VRT technology and adoption for greater efficiency.

The problem lies in precisely understanding nutrient demand, as VRT application has outpaced the current capabilities of nutrient mapping.[6] VRT systems use advanced methods to predict demand, including remote sensing with satellite and drone imagery, lab soil composition testing,[7] in-situ soil nitrate testing,[8] and yield mapping.[9] However, these methods remain disjointed, lacking the complete and timely data necessary for optimal nutrient management. Still, future technology is gaining traction: as of 2023, nutrient surveyance UAVs were offered by 55% of agricultural service providers in the U.S., with presence anticipated to reach 75% by 2026.[4] Likewise, precision fertilizer sprayer drones are rapidly emerging, with a projected annual market growth of 20%.[10] These trends reflect the growing need for automated, data-driven nitrogen management solutions that are both accessible to farmers and seamlessly integrable with existing technologies.

II. Use Case and Proposed Solution

A. Problem Statement and Identified Need for System

Nitrogen is the most critical nutrient required for plant growth, yet it remains a limiting factor in crop production due to limited bioavailability: plants cannot absorb the more abundant organic N and are limited to inorganic forms such as nitrate.[11] While N-fertilizers support high yields, overapplication and high nitrogen losses, often up to 50%, result in environmental harm.[12] Nitrate leaching contaminates water systems, leading to freshwater and coastal eutrophication.[13] Nitrogen fertilizers are also a primary source of nitrous oxide (N_2O), a GHG with a global warming potential 298 times higher than that of carbon dioxide.[14] Agronomic management practices, such as targeted fertilizer application, mitigate these environmental risk factors.[12]

Current nitrogen testing methods present significant limitations. Conventional soil sampling is accurate but time-, resource-, and labor-intensive. Non-invasive remote sensing methods, including satellite imagery and UAV spectroscopy, offer rapid results, but measure nitrogen indirectly and are prone to inaccuracies. These fragmented methods, used in isolation, fail to provide a comprehensive, accessible solution for farmers. There is thus a clear need for a system that can combine the in-situ accuracy of physical soil sampling with the speed of real-time spectral analysis while unifying nitrogen management technologies into a cohesive, user-friendly platform to support targeted fertilizer application.

To address this need, the proposed system delivers precise, real-time nitrogen data through multi-scale analysis and integrates with precision mapping to provide targeted fertilization and sustainable land management.

B. Proposed System

The proposed aerial system, *PLAANT*, integrates existing and emerging technologies to deliver real-time, accurate soil nitrogen data and automated fertilizer application. By uniting cross-scale nitrogen sampling—satellite imaging for broad variability insights, UAV-based multispectral spectroscopy for finer resolution, and in-situ physical soil sampling for tailored calibration—*PLAANT* provides a comprehensive analysis of field conditions (*Fig. 1*). Physical, spectral, mathematical, and machine learning techniques inform geotagged nitrogen data that is integrated into precision mapping platforms, enhancing model accuracy and supporting long-term management strategies. This enables specialized fertilizer recommendations and automated application, improving short-term productivity, reducing waste, mitigating environmental impacts, and promoting long-term sustainable and predictive farming practices.

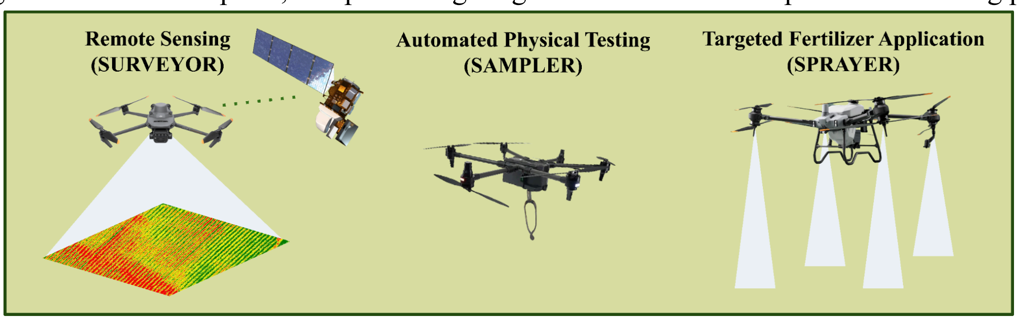


Figure 1: Three Main UAV-driven Phases of Proposed System.

1. Use Case

Optimized for mid- to large-scale (≥400-acre) high-production agriculture, *PLAANT* addresses operations that contribute over 80% of U.S. crop production.[15] Corn, soybeans, and cotton are noted as ideal system applications due to their high production, use of N-fertilizer, and potential for existing PA infrastructure.[15] However, *PLAANT* is tailored to size, with the capability to downsize or integrate additional UAVs into a connected unmanned aerial system (UAS) with a scalable range.

Operational requirements include climate-controlled storage, transportation, flight operations, and data management. Climate-controlled storage prevents lithium-ion battery and reflectometer degradation, while chemical nitrate test reagents require refrigeration for long-term storage and should be loaded just prior to deployment.[16-17] Beyond operation, *PLAANT* will be stored on an indoor parked vehicle for controlled conditions and ease of deployment. Operations will require proper operator licensing, while data will be managed by the service provider and shared with the client or other stakeholders as needed.

2. Design Considerations

Effective nitrogen testing, a stable drone platform, optimal sampling parameters, and user experience were key design priorities. Nitrate strip tests were selected for cost-effectiveness, rapid results, and ability to perform in-situ testing with minimal preparation.[18] The sampler UAV's drone design provides extended flight time and payload capacity for full sample coverage.[19] Servicing will occur biweekly during peak growing months (May-August) and monthly during planting and harvesting.[20-21]

One-foot sampling depth ensures an accurate representation of sub-surface nitrogen data at relevant uptake locations. Approximately 40% of nitrogen is available within 1 foot from the soil surface.[22] The system's use of mapping and simulation will extend to model N distribution throughout the soil, below sampling depth, for extended prediction and reduced bias in soil results.

Thoughtful design and seamless integration of the automated auger and actuation system ensure reliable sampling without compromising aerial performance. Forces experienced during sampling are a key concern for proper UAV operation. To this end, the Edelman auger minimizes stress on the drone during soil collection and stabilizing anchors on the landing gear provide added security during sampling. Augers will be interchangeable to accommodate different soil types as needed, at the discretion of the soil technicians. The auger will be stored inside the UAV fuselage during flight, and excess soil on the auger between samples will be removed by brushes upon retraction to mitigate sample contamination.

Optimal annual nitrogen rates for peak yield of corn, soybean, and cotton are 240 lb/acre, 126 lb/acre, and 70 lb/acre of granular nitrogen, respectively[23]-[25]; this is equivalent to 800, 420, and 233 lb/acre of liquid ammonium fertilizer[26]. Maintaining these optimal rates consistently across fields is strongly correlated to increased yield and minimized variability of crop growth across the field.[27] Emerging research shows that low frequency, high dose applications, 1-3 visits/yr, result in low NUE, increasing leaching.[28] Thus, *PLAANT* will use an application frequency of 16 visits/yr, allowing crops to fully intake smaller doses while still achieving the optimal rate, significantly improving NUE.[6]

C. Existing Technologies

Existing technologies provide the foundation for an encompassing solution.

1. Soil Mapping Software (TRL 9)

A key PA management tool is soil mapping for various nutrients, including nitrogen, which informs subsequent VRT management practices (*Fig. 2*).[29] Maps are created using geotagged sensor data through geographic information system (GIS) and Global Positioning System (GPS) capabilities.[30-31]

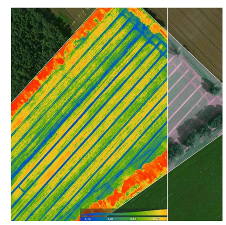


Figure 2: Pix4D Soil Map[32]

2. Satellite Remote Sensing (TRL 9)

Satellite remote sensing assesses nitrogen status by detecting variations in plant reflectance across visible and near-infrared wavelengths and producing vegetation indices, such as the normalized difference vegetation index (NDVI) and normalized difference red edge (NDRE), which indicate N-dependent crop vigor and chlorophyll content.[33] This large-scale, non-invasive method enables consistent and accessible field variability assessment, but is limited by cloud cover, low spatial resolution, and indirect nitrogen measurement.

Figure 3: Edelman Field Auger [34]

3. Edelman Auger (TRL 9)

Long favored in agriculture for ease of use and sample preservation, the Edelman auger is isolated for aerial application within the *PLAANT* system due to its simplicity, flexibility, and low extraction force compared to other probing methods (*Fig. 3*).

4. Chemical Test Method for Soil Nitrogen Analysis (TRL 9)

Colorimetric nitrate test strips are widely available with reliable accuracy. This test method involves mixing soil and deionized water in a 1:1 ratio, allowing soil particles to settle, and immersing the test strip in the solution. An indicator causes the strip to change color based on the nitrate concentration, which can be measured using a spectrometer to obtain quantitative results.[18][35] The testing process will be modified for aerial use by reducing the test sample volume and replacing the settling step with a filtration operation to increase speed.

5. Sprayer Drones (TRL 9)

Drones equipped with fertilizer tanks and precision VRT nozzles apply fertilizers and chemicals directly to targeted areas using GPS guidance. They improve application efficiency, prevent waste, and minimize soil compaction compared to traditional ground equipment.

6. Support Technology – Nano Color Spectrometer & RTK Base Station (TRL 9)

A nano visible light spectrometer with a 400–700 nm range will scan the violet intensity of the test strip and determine the corresponding nitrate concentration.[35] Real-time kinematics (RTK) stations increase drone GPS positional resolution from 5 m to under 2 cm,[36] increasing data mapping accuracy.

D. Emerging Technologies

Emerging technologies enhance the system's capabilities to further precise nutrient management.

1. UAV N Spectroscopy (TRL 9)

Spectroscopy analysis uses high-resolution imaging to measure wavelength reflectance from chlorophyll in crop leaves, correlating to photosynthetic activity and nitrogen uptake.[37] UAVs equipped with multispectral or hyperspectral sensors enable real-time analysis over large areas, optimizing nutrient management with minimal disruption.[38] However, environmental factors and variations in leaf structure, shape, and size can influence accuracy, and application is limited primarily to post-emergence.[37]

2. Multirotor UAV with Auger Actuation System (TRL 6)

Fixed-wing and rotorcraft drones are used for agricultural surveillance, mapping, spraying, and other uses.[39] Multirotor UAVs have become favored for commercial applications due to low cost and ease of use. Their hovering capabilities, even frame weight distribution, and sufficient speeds make them favorable for PA missions. After analysis of the system's demands, *PLAANT* employs this subclass for the entire UAS. Currently, researchers are developing multirotor drones with soil sampling augers.[70]

3. Improved 500 Wh/kg Battery Energy Density (TRL 4)

Current rechargeable lithium-ion batteries for drone use have an approximate energy density of 150 Wh/kg, with energy density anticipated to reach 500 Wh/kg by 2035.[40] *PLAANT* surveyor and sprayer UAVs will be powered by replaceable, rechargeable batteries to ensure easy and continuous drone operation. Utilizing the most advanced commercially available batteries and increasing energy densities over time will extend flight times and reduce the number of batteries needed on site.

III. Implementation

A. Concept of Operation

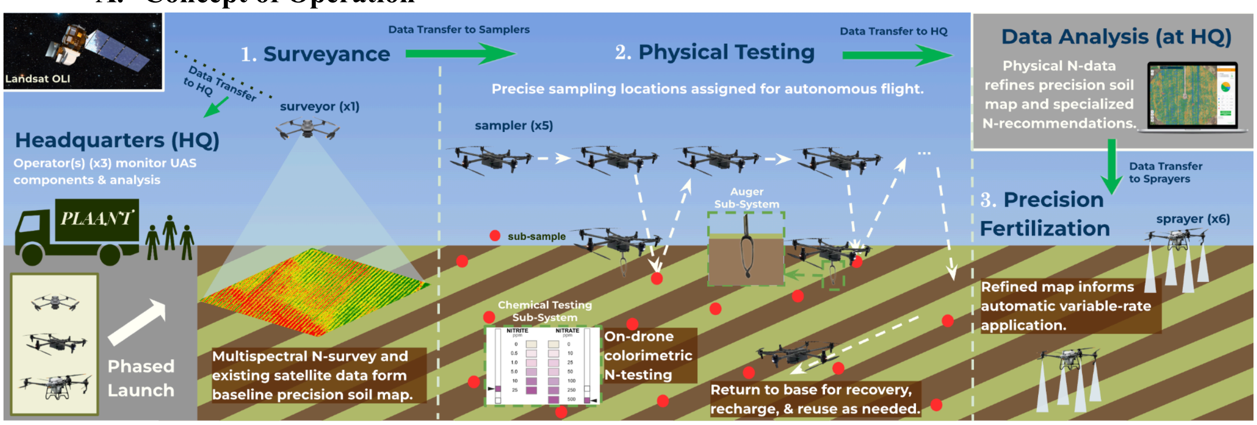


Figure 4: Operational Concept of PLAANT system, showing phased approach and data transfers.

The *PLAANT* system provides an automated solution to measure soil nitrogen levels and optimize fertilizer use through several operational states (*Fig. 4*) [*Table B.1-B.2*]. Operation and timing here are charted for the 400-acre farm scale section:

Preparation: Off-site, two soil technicians segment the field into 20-acre uniform management zones and identify soil type for appropriate auger selection. Software (e.g. Pix4D) is used to define autonomous flight paths for the multispectral surveyance UAV. On-site, four technicians and three drone operators prepare the mobile control station, with setup time estimated at 30 minutes.[42]

Surveyance with Surveyor UAV(s): An operator deploys the multispectral drone to autonomously survey the field at an altitude of 30 meters, covering 400 acres in 14 minutes. The drone captures inferred nitrogen absorption data based on crop health activity. Imaging data is transmitted in real time to the control station and processed using PA algorithms, additionally refining the sequences of the samplers.[37]

Physical Testing with Sampler UAV(s): Utilizing satellite imagery and multispectral drone data, the sampler drones are assigned 15 takeoff and landing sequences per 20-acre zone, aligning with United States Department of Agriculture (USDA) sampling density recommendations for cereal crops.[41] Backup sampling sites are also determined in case of non-viable sampling, with all waypoints aiming to fill perceived data gaps in N visibility. Two operators launch 5 soil sampling UAVs to collect 15 samples from each 20-acre plot. Each UAV (36” frame width) lands between crop rows and deploys a retractable auger to extract a 1-foot soil core.[43] With machine learning and motion sensing feedback, the sampler detects potential obstructions and is able to proceed to a backup sampling site if needed.

The sample is homogenized onboard, retaining 2 grams for testing while discarding excess soil.[12] Deionized water stored in the drone's fuselage is mixed with the soil sample, filtered, and applied to a colorimetric nitrate test strip. A micro-spectrometer analyzes the color change, and the onboard microcontroller interprets the result.[18] Geotagged data is transmitted to the control station.[35] The sample mixture is discarded, and the drone proceeds to the next waypoint, sanitizing the auger between samples. With 5 samplers,[42] the 400-acre area is serviced in eight hours with all drones within line of sight.

Data Analysis and Precision Fertilization with Sprayer UAV(s): At the control station, a NUE model is generated from the physical sampling and multispectral data with soil mapping software, indicating the ratio of plant nitrogen uptake to soil nitrogen content. Two operators will then launch 6 fertilizer sprayer drones to apply variable nitrogen rates to areas with NUE greater than 1.[42][119] Each sprayer will deploy an average baseline of 50, 26, and 15 lb/acre of liquid nitrogen fertilizer per visit for corn, soybeans, and cotton respectively [*Table B.4*], and with varied spray rates based on NUE model recommendations. With a 6.5 gallon capacity and a nominal spray rate of 2 gal/acre,[44] sprayers will be refilled and deployed every 6-8 minutes, comparable to current market commercial sprayers[44]. For corn, soybean, and cotton, an average of 4.6, 2.4, and 1.3 gal/acre of fertilizer is deployed, respectively, resulting in a coverage of 1.4, 2.7, and 4.8 acres before each fertilizer refill [*Table B.4*]. Application time is 3 hours, assuming each drone covers 16.5 acres per hour, but variability due to N recommendations is expected.[45]

Cost and technological integration are the main barriers to the adoption of PA technology.[4] This reality was emphasized after consultation with several leading figures in region-specific soil analysis and precision agriculture: Professors Kumar[123], Zhu-Barker[124], and Khosla[6]. Drone sizing specifications are detailed in Appendix *Table B.3*, while future efforts would continue to focus on a sophisticated analysis of the development and operational capabilities of each component and interoperation. To support adoption, *PLAANT* prioritizes system usability and full-scope integration, with features such as removable sensor mounts and emergency auger ejection to guarantee seamless maintenance. Cost concerns are mitigated through program incentivization and prioritization of farmer profits, achieved via increased yield, improved resource efficiency, and environmental conservation.

B. Interoperability with Existing Processes and Technologies

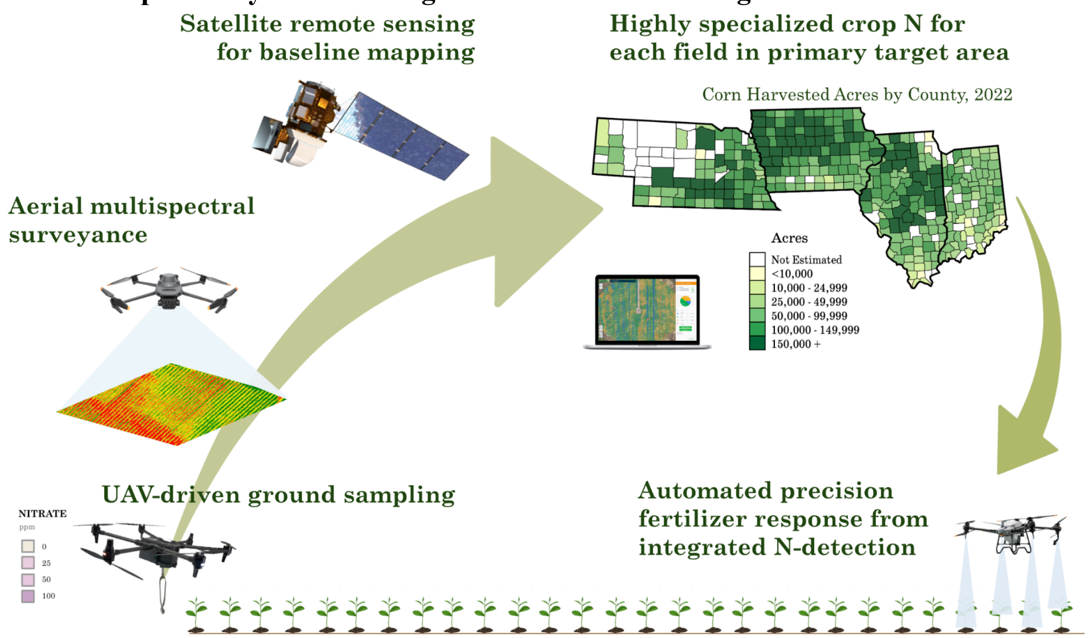


Figure 5: Integration of cross-scale nitrogen analysis for improved mapping and precise response.

1. Technology Integration

PLAANT will integrate with existing precision agriculture technologies, including yield mapping, automated guidance, and VRT application systems.[46] This cross-scale technological integration is illustrated in *Figure 5*. Soil nitrate information generated by *PLAANT* will be synthesized with multispectral UAV surveyance, satellite-based remote sensing, and historical field data to enhance nitrogen demand modeling and fertilization precision. Satellite remote sensing offers broad nitrogen trend analysis and long-term monitoring, while multispectral UAVs provide high-resolution, real-time variability mapping through plant reflectance analysis. Physical soil sampling further refines this nitrogen model by delivering localized, high-accuracy nitrate concentration data. The cross-scale approach refines a baseline model to tailored field accuracy. Interfacing with PA software, these datasets are combined to form adaptive fertilization strategies with improved accuracy. Existing and commercially available applications can assimilate data from multiple sources, requiring minimal development for integration.[47]

2. Connectivity Constraints

Connectivity constraints for *PLAANT* address broad GPS resolution and communication and control range limitations. An RTK base station will improve this resolution from 5m to 2cm.[36][48] To address communication, a long-range tracking antenna system is mounted to the mobile control station, increasing the range between the control station and UAVs to 60 km.[49] Should the GPS signal or RF transmission fail, fixed flight path waypoints will allow the drone to continue its planned mission and the drone will save data with SD card memory.[47] GNSS and RTK technology are commercially available for automated vehicle guidance in precision agriculture,[50] and for small UAVs.[51] The generated fertilizer recommendations are seamlessly executed using aerial equipment with automated guidance.

3. Operator Training

Operators must hold an FAA Part 107 Certificate for commercial UAV piloting. Training will include UAV/UAS operation, maintenance, data handling, and external system integration. Operators are the primary liaison between the *PLAANT* service and clients, ensuring effective use and satisfaction.

4. Public Education

During development, the USDA will promote educational programs based on *PLAANT* research. These programs, distributed through their agencies and Cooperative Extension System (CES) member universities, will educate both farmers and stakeholders on *PLAANT*'s economic and environmental benefits to increase adoption.

5. Stakeholder Involvement

The team has identified key stakeholders across agriculture, technology, and regulatory sectors to support system development, implementation, and deployment. Farmers serve as end-users, providing feedback during the design and pilot phases. Collaboration with PA companies and software providers ensures seamless integration into existing platforms, while regulatory agencies such as the FAA and EPA will oversee aviation and sustainability compliance. Academic institutions and government agencies, including the USDA—and sub-agencies: National Institute of Food and Agriculture (NIFA), Agricultural Research Service (ARS), National Resource Conservation Service (NRCS)—and international organizations including the Food and Agriculture Organization of the United Nations (FAO) and the International Fund for Agricultural Development (IFAD) will support validation, funding, and incentivized adoption with established programs and rural outreach efforts. To guide development, the team has consulted experts with specialties ranging from remote sensing, to ecological modeling, PA, nitrogen management, and government agricultural programs. These engagements have refined *PLAANT*'s design, sampling methodologies, and integration strategy, while validating the design throughout. These meetings aimed to prioritize system alignment with the forefront of research, technology, policy, and sustainable agriculture practices. See Appendix *Table C.1* for consultation notes.

C. Cost Analysis

A Rand Report cost analysis [52] was conducted for *PLAANT* for non-recurring research, testing, development, and evaluation (RTD&E), and a recurring cost analysis (Operation, Maintenance, Fixed Equipment, Transportation, Training) was performed alongside a drone mission and sizing analysis [*Table B.3*].

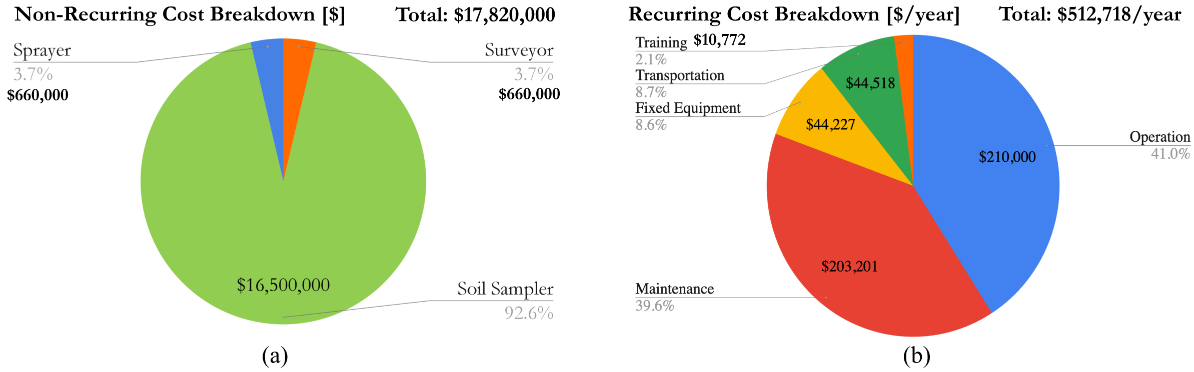


Figure 6: (a) Non-recurring (RTD&E) cost breakdown [$], (b) Recurring cost breakdown [$/yr] [Table D.1].

Based on a breakdown of the costs, non-recurring costs to create a 400-acre prototype system total $17.8 million, and annual recurring costs total $513,000 per system *(Fig. 6)* [*Table D.1*]. In non-recurring costs, the soil sampler drone maintains the largest RTD&E due to a lack of existing commercial viability. Among recurring costs, operation and maintenance expenses are largely attributed to labor, and transportation expenses to the price of fuel [*Table D.2*]. By aerially automating the sample and test process, *PLAANT* is calculated to reduce labor costs of soil sampling services by 15%, accounting for analysis of samples on the spot [*Table D.5*].

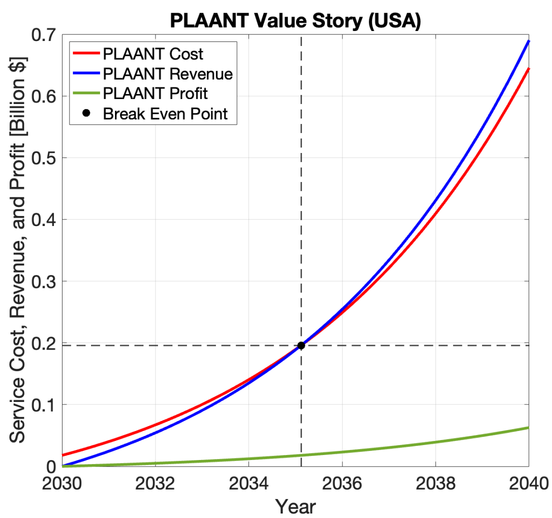


Figure 7: PLAANT value story, 10% profit margin.

Annual expenses in the U.S. for nitrogen fertilizer are currently $12 billion[53-54]; annual profit from corn, soybean, and cotton totals $139 billion.[55] Adoption of superior nitrogen management would facilitate a potential reduction of 35% nitrogen fertilizer and increase annual crop yield by 20%.[56] This system scales linearly, with savings and profit increase estimated per acre, at $14.04 and $92.90, respectively. Projecting a 30% adoption rate by 2054, net savings are estimated at $1.23 billion in nitrogen expenses and an increase in annual aggregate corn, soybean, and cotton crop profit of $8.4 billion in the U.S. [*Table D.3*].[55]

PLAANT will launch in 2030 with a 10% profit margin and reach its break-even point in 2035, having serviced 1.35 million acres of cropland (Fig. 7`). This translates into an adoption rate of 0.45%, equivalent to 3,366 medium-sized (400-acre) farms. This projection corresponds to a profit of $17.8 million, the value required to fully pay back all non-recurring costs (*Fig. 7*). At the break-even point, farmers in the U.S. are calculated to increase yield by $16.2 million and save 4.4 million pounds of fertilizer (at $0.55/lb) [*Table D.4*]. With an annual service price of $100.68/acre and an increased farm revenue of $106.60/acre from increased yield efficiency and N savings, farms can reasonably afford PLAANT and increase their profit from service use (*Fig. 8*); these results translate into a return on investment (ROI) of 6.4% for the farmer [*Table D.4*]. With a 9-year break-even payback period from full US launch in 2030, *PLAANT* is calculated to have an ROI of 17%. Assuming a 3% discount rate, the sum of non-recurring

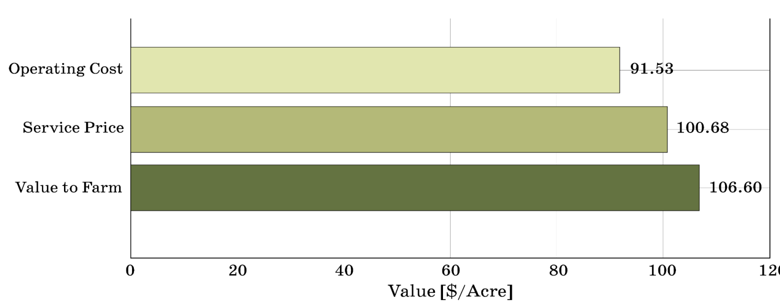


Figure 8: PLAANT service expenses, PLAANT service price, and farmer revenue [$/Acre].

cost and net income over 10 years (2030-2040) has a net present value (NPV) of $29.2 million [App. D].

D. Business Implementation

PLAANT will be launched through licensing to a variety of commercial PA service companies (e.g. John Deere, Hylio Inc.) and by USDA Technical Service Providers (TSPs). Equipment will be manufactured and stored in approximately 10 centralized locations across different regions of the U.S. When used, system equipment will be leased to service providers, who will operate *PLAANT* systems with their own drone operators and technicians to provide the *PLAANT* service to farmers. Equipment lease contracts will be set at a minimum of a one-year period, and contracts can be renewed indefinitely.

As of 2022, the agriculture UAV market is 5% of the entire UAV world market,[57] with the U.S. agriculture drone market comprising 30% of the total agriculture UAV market.[58] With a general PA adoption rate of 27%, estimations with an S (Sigmoid) curve analysis can be used to predict the U.S. PA adoption rate to reach 50% by 2030. Assuming the same growth rate for the *PLAANT* system, predicting a conservative estimate of 5 years to 0.45% adoption allows the system to reach 30% adoption by 2054.

IV. Path to Deployment

A. Technology Readiness Levels

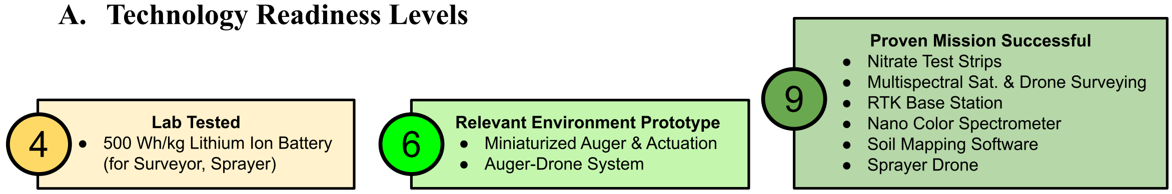


Figure 9: PLAANT Component Technology Readiness Levels Summary

Technology components critical to *PLAANT's* operations were evaluated through NASA's TRL framework [*Table E.1*][59] (*Fig. 9*). *PLAANT's* innovation lies in the unification of the mature technologies (TRL 9) and the emerging technologies proposed to introduce the novel soil sampling UAV. Battery density (TRL 4) is anticipated to increase through 2035, and the auger system (TRL 6) will further develop during *PLAANT's* R&D. System feasibility is further substantiated by proof-of-concept efforts under NASA consortiums Acres and Harvest, such as with the Acres-led *Remote Sensing and Agroecosystem Modeling to Support Sustainable Nitrogen Management in the Midwest* project.[60] The team was advised by NASA Acres researcher, Professor Sheng Wang, on best practices in this area.[125]

B. Opportunity and Barrier Analysis

1. Licensing and Regulation

Deployment will require compliance with Section 2230 of the FAA Extension, Safety, and Security Act of 2016 for component manufacturing. Service providers adopting *PLAANT* must establish FAA Business DroneZone Accounts to manage fleet operations and ensure Remote ID compliance under Part 89. As previously stated, operators will need a Part 107 certification waiver 107.35 and a section 44807 exemption, allowing 1 operator to control 3 drones that are each under 165 lb.[42] Additionally, Part 137 and Part 135 certifications will be required to regulate proper soil collection and disposal procedures. A beyond visual line of sight (BVLOS) waiver may be required depending on site size. Federal programs, including the Agriculture Improvement Act of 2018, the Environmental Quality Incentives Program (EQIP), and the Conservation Stewardship Program (CSP), can assist with funding to support technology adoption and service costs for farmers [*Table E.2*].

2. Legal Analysis

The system will address risks relevant to FAA airspace restrictions and required detect-and-avoid technologies for safe operations by maintaining constant, low-altitude flights (<170 ft above ground).[61-62] Services using *PLAANT* will address data privacy and ownership challenges through data contract agreements between the service provider and the client. To address the auger-drone system as a novel intellectual property and a licensing concern, *PLAANT* will apply for patents upon successful testing in a farm environment. Trial testing will be used to refine the system accuracy of *PLAANT,* ensuring environmental compliance under EPA regulations. Comprehensive insurance purchased by the service provider will protect against liability concerns such as crashes, crop damage, or test inaccuracies.

3. Risk Analysis

The team analyzed the risk of various categories and evaluated risk severity and frequency with and without abatement [*Table E.3-E.4*]. The highest two risks posed to the system are environmental impacts and potential drone collisions. To mitigate extreme heat, wind, or sudden passing rain, drones will have temperature and flow sensors to ensure outside conditions do not exceed the heat and wind tolerances of the drone.[63-64] In the event of passing rainfall, drones will be equipped with liquid ingress coating,[65] allowing them to temporarily abort the mission and safely return to the docking station. To mitigate the probability of collisions, drones will be equipped with proximity and ultrasonic sensors that will feed data to obstacle collision prevention algorithms.[66] Drones will fulfill missions in swarms of 3, keeping drones with similar flight paths close together and those with different flight paths far apart.[67] The risk of drone destabilization is minimized by proper weight distribution and adequate 30-second takeoff and landing sequences.

a) Crop Canopy Analysis

Crop canopy formation will be a key risk for *PLAANT* to address. Crops such as corn can grow to be 1 ft tall within one month of being planted and grow to their full height within 2 months, growing dense canopies quickly.[68] Corn stalks at growth nodes have an average bending moment of 9.6 lbf [69] and leaves will have lower bending moments than the stalks. *PLAANT* soil sampling drones will weigh approximately 108 lbs [*Table B.3*], allowing for plenty of necessary force for landing and takeoff through leaves. The drone may also be equipped with optional propeller guards, at the discretion of on-site staff, to protect the rotors from damage, with the understanding that this will slightly decrease performance.

Backup sampling locations are pre-designated to ensure continued operation in the event of significant canopy obstructions along the primary sample path. Should canopies pose a greater risk than anticipated after further research and field testing, a separate soil sampler may be developed, where the drone will hover above the crops and lower a sampling apparatus through the crop canopy. This system has been demonstrated by the *Terra-22* Canadian research team from the Université de Sherbrooke.[70] *PLAANT* may need to consult legal experts to avoid ownership conflicts when developing this solution.

4. Environmental Analysis

Current and near-future batteries cannot sustain soil sampling drones for long-term flight missions because they would require a significant drone empty weight fraction (>0.7). Thus, to maintain an optimal lift-to-drag ratio and reasonable empty weight fractions, soil sampling drone rotors will be gas-powered until improvements in battery technology can sustain long flights, with supporting components (e.g. auger, sensors) powered by a small 50 Wh battery. An analysis of CO_2 emissions for drones reveals an average of 0.00441 kg CO^2/km.[71-72] Taking into account *PLAANT*'s sampler drone fleet, the aggregate emissions will still be 12.5% less than tractors [*Table D.6*].

PLAANT directly improves NUE, addressing the environmental harm caused by conventional N-fertilizer application. Improved NUE lowers overall fertilizer demand, reducing the carbon footprint associated with the full lifecycle of N-fertilizer, from manufacturing, to application, to nutrient cycling. From a cost standpoint, EPA data reveals that nitrogen and phosphorus eutrophication result in $2.4 billion spent on annual freshwater treatment.[73] 78% of U.S. nitrogen and phosphorus eutrophication is attributed to agricultural fertilizer leaching and runoff.[120] Between the combined contribution, nitrogen accounts for 90% of the leaching, with research showing nitrogen content leached to be 10 times that of phosphorus.[74] Thus, *PLAANT's* ability to reduce up to 35% of Nitrogen fertilizer use has the potential to translate into an annual reduction of $150 million spent on water eutrophication treatment.

Production and use of synthetic nitrogen fertilizers in the U.S. create 116 Mt CO_2eq emissions annually.[121] Effective targeted N application is proven to reduce N_2O emissions, with field studies as early as 2003 indicating VRT can reduce N_2O by 34%.[75] In addition to runoff-induced eutrophication, targeted nitrogen application also prevents wider ecosystem destabilization and subsequent methane emissions. *PLAANT* helps combat the projected 30-90% CH_4 emission increase over the next century.[76] The service impact of *PLAANT* is expected to reduce U.S. agricultural GHG emissions by 13 Mt CO_2eq annually. With this, *PLAANT* offers a scalable, sustainable solution to minimize agriculture's environmental footprint and support climate resilience in a growing world.

C. Timeline to Deployment

The deployment of *PLAANT* follows a 3-phase strategy, with R&D and early testing in the U.S. corn belt states, large-scale deployment aiming for full U.S. deployment, and initial efforts for global deployment in countries with existing PA infrastructure *(Fig. 10)*.

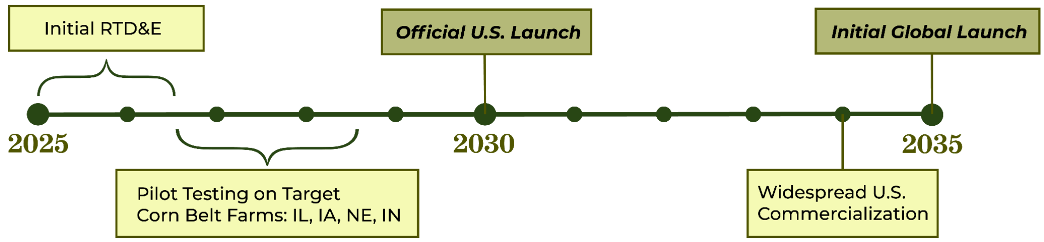


Figure 10: 10-Year Deployment Timeline with Key Milestones.

Phase I will start in 2025. Between 2025 and 2026, *PLAANT* will undergo rapid research and development to be ready for initial deployment in 2027. At this point, site-specific testing in the Corn Belt will begin on farms in Champaign, Illinois; Benton, Iowa; Tippecanoe, Indiana; and Lancaster, Nebraska. These 4 sites were selected for their high corn yields, non-irrigated fields (ensuring above-ground fertilization), and proximity to robust land-grant institutions with developed PA and agronomy departments (University of Illinois Urbana-Champaign, Iowa State University, Purdue University, and the University of Nebraska).[78] Through the end of 2029, *PLAANT* will expand throughout the region while testing and refining operations. Large-scale testing during this period on high-production farms in the extended region will help to optimize system reliability, usability, and data integration. These expanded tests will focus on farms in Illinois, Iowa, Nebraska, Kansas, North Dakota, and South Dakota, due to developed precision agriculture adoption and utilization of over 40%.[77]

By 2030, Phase II will begin, and *PLAANT* will have its official commercial launch across the United States. *PLAANT* will aim to deploy outward from the corn belt to farms in states with high PA adoption percentages first, with deployment supported by USDA programs such as NIFA and NRCS. Registration with NRCS as a Technical Service Provider (TSP) will aid in national rollout, as the *PLAANT* team was advised by the Midwest TSP coordinator, Miguel Oliveras.[79] Full nationwide deployment is targeted by early 2034, corresponding to broad deployment to farms and service providers.

Phase III will initiate global expansion, beginning in 2032, continuing into 2035 and beyond. Global expansion begins with region-specific R&D between 2032-2033 and the launch of pilot programs in locations with previously established PA infrastructure, including parts of Europe, Asia, and Oceania by 2034. During this time, *PLAANT* will build partnerships with local organizations to assist in addressing regional agricultural conditions and adoption by farmers. As the system maintains widespread U.S. deployment, the official global launch in 2035 advances sustainable nitrogen management, resource conservation, and agricultural productivity. Given the growing demand and adoption rates for PA solutions, *PLAANT* has a promising opportunity space to secure a substantial market presence, reaching up to 30% potential U.S. adoption by 2054.[4]

V. Conclusion and Expected Improvements

The *PLAANT* system advances PA by reducing the expenses, time, and labor associated with traditional manual grid sampling, connecting a disjointed system to streamline nitrogen management. Integrating multispectral analysis with in-situ soil sampling, *PLAANT* significantly improves the accuracy of nitrogen-specific indices like NUE, using measured soil nitrogen content as a direct reference rather than sole reliance on remote data. The subsequent automated VRT fertilizer application allows for accessibility in adopting a full-scope nitrogen management solution, reducing the PA barrier to entry and streamlining nitrogen management. This combination of efficiency, accuracy, and scalability reduces operational costs, optimizes nitrogen management, and promotes sustainable agriculture. *PLAANT* empowers farmers to increase yields, reduce environmental harm, and drive the transition toward clean, smart, data-driven agriculture.

Appendices

Appendix A

Down-Selection of Technical Areas

Table A.1: Pugh Matrix quantifying key metrics of each technical area.

Metrics:

Technical Area:	*Opportunity*	*Cost*	*Scope*	*Technology*	*Environment*	*Future Trend*	*Total*
Cropland / Rangeland Surveyance + Conservation	3	3	9	3	3	9	30
Pest & Disease Management	3	9	9	3	9	3	33
Agriculture Inspection	3	3	3	3	1	3	16
Targeted Fertilizer Application (Selected Area)	3	9	9	3	9	9	42
EAVs (Essential Agriculture Variables)	3	3	3	3	3	3	18
Autonomous Missions	3	3	1	3	1	3	14
Livestock Management	3	9	3	3	3	3	24
Improved Weather Accuracy	3	9	9	3	9	9	42

Legend: Impact of New Innovation/Technology

1 – Least impactful

3 – Somewhat impactful

6 – Moderately impactful

9 – Most impactful

- Selected area

Appendix B

Operational Specifications

Table B.1: Concept of Operations (ConOps) Process Specifications (for 20 acres)

Process	Process Description	Operation Time [min]
Set-Up	Unload equipment from the truck, set up RTK station, power on drones	30
Surveyor Drone Flight	Initial visual surveyance 20-acre grid	0.68[80]
Soil Sampler Drone Takeoff/Landing	Takeoff and Landing (30 sec per sequence) before and after soil sampling	7.5[81]
Auger Soil Collection	Time for auger to actuate, drill, collect 15 two-gram soil cores, and retract (2 min per core sample)	30[81]
Nitrate Strip Test	Test conducted with drone on ground for each of the 15 soil cores (6 min per test)	90[18]
Soil Sampler Drone Flight	Total flight time for drone traveling between 15 soil collection sites (15 cores total) (approx. 6 sec travel between each sampling site)	1.5[82]
Sprayer Drone Flight	Total flight time to apply fertilizer over 20 acres	30[44]

Table B.2: Time/Effort for Surveying and Sampling missions of PLAANT (for a 20-acre plot)

Mission Details	Metric	Comments
Total Mission Time for Multispectral and Soil Sampling (time spent at one 20-acre plot)	129.1 min	Excluding Set-Up Time
Surveyor Drone Flight Time	0.68 min	Total flight time to survey 400 acres is 13.6 min
Soil Sampler Flight Time	8 min	Including Takeoff/Landing and Traveling Time
Time Spent on Ground	120 min	Including Auger Soil Collection and Nitrate Test Time
Drone Battery Life	240 min	Reference[82]
Maximum 20-acre plots covered by 1 sampler drone	4 plots	Theoretically, the sampler drone can cover 5, but 4 is the realistic maximum to compensate for adverse weather conditions and fuel consumption
Drones per Operator	3	Reference[42]

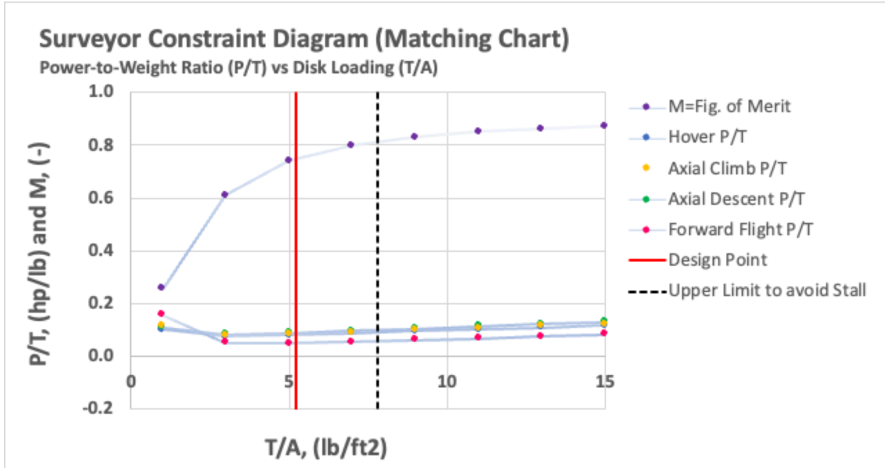
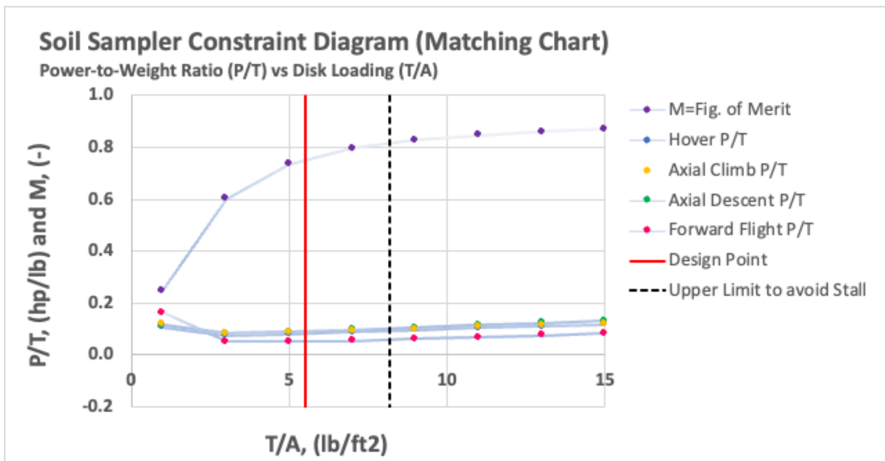
Table B.3: Drone Sizing Characteristics for Surveyor, Soil Sampler, and Sprayer [83-84]

Characteristic	Surveyor	Soil Sampler	Sprayer
Gross Weight [lb]	1.90[85]	108[44]	163[44]
Frame Dimensions [ft] (L x W x D)	0.40 x 0.40 x 0.1	3.0 x 3.0 x 0.43	4.5 x 4.5 x 0.6
Rotor Diameter [ft]	0.3	2.0	3.3
Empty Weight [lb]	1.158	18.8	96.7
Payload [lb]	0.235[62]	20[82]	70.0[86]
Energy Weight [lb]	0.545	0.3[87]	22.6
Battery [Wh/kg]	150 [40]	–	150[40]
Recharge Time [min]	35 min[85]	–	120 min[44]
Gas Fuel (per Flight) [lb]	–	0.3	–
Flight Speed [ft/s]	119.8[115]	59.1 [82]	43.9 [44]
Endurance [min/flight]	20 [*Table B.2*]	64	8.0 [86]
Lift/Drag Ratio	4.23	4.22	1.02
Height above Ground [ft]	164 [62]	29.5 [86]	29.5 [86]
Survey Grid Size [acres]	5.23 [80]	–	–
Acre Coverage [acres/hr]	1767	10 [Table B.2]	16.5 [44]
Spray Rate [lb/acre] [72]	–	–	Nominal 17.5-22, (0.25 – 15) gal/acre
Drone Service Life [year]	2	5	5

Table B.4: Average baseline application rates of Sprayer Drones

Category	Corn	Soybean	Cotton
Granular Rate/yr [lb/acre]	240 [23]	126 [24]	70 [25]
Liquid Rate/yr [lb/acre][26]	800	420	233.3
Liquid Rate/yr [gal/acre][26]	73.7	38.7	21.5
Rate Applied per Visit (16 visits per year) [gal/acre]	4.60	2.42	1.34
Sprayer Rate [gal/acre][71]	2		
Sprayer Tank [gal][71]	6.5		
Acre Coverage Per Refill [acre]	1.41	2.69	4.84

Table B.5: Sizing Drone L/D Design Plots [83-84]

<table>
<tr><td>Surveyor Drone</td><td>
</td></tr>
<tr><td>Soil Sampler Drone</td><td>
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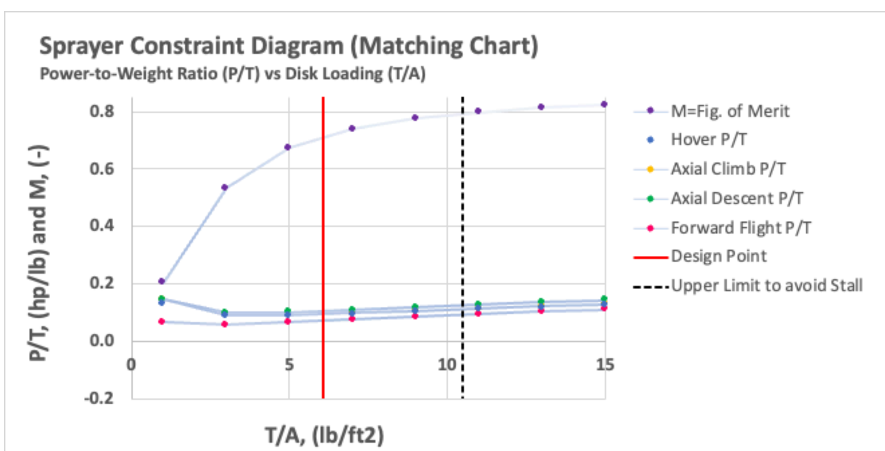
<tr><td>Sprayer Drone</td><td>
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Appendix C

Expert Insights

Table C.1: Expert Interview Summary

Expert	Institution	Date	Key Insights
Prof. Mark Friedl	Boston University *Earth & Environment*	10/10	The co-founder of a startup involving crop yield forecasting using satellite-collected weather data. Additional info on weather forecasting and prediction models, extreme weather impacts, and AI models.
Prof. Michael Dietze	Boston University *Earth & Environment*	10/14 11/5	Information regarding physical soil sampling and measurements, GHG emissions, multispectral and hyperspectral sensing technologies, data assimilation techniques, and relevance of different nitrogen types.
Prof. Kenn Sebesta	Boston University *College of Engineering*	11/4	Battery life of the drone, accounting for drone weight, deployment of the auger, and advised development of sampler stability measures.
Prof. Hemendra Kumar	University of Maryland *College of Agriculture & Natural Resources*	11/11	Information regarding nutrient variability, interfacing between existing precision agricultural software and technology, and the combination of physical and sensor measurements. Recommended focusing on the U.S. to begin, as U.S. lags in certain areas of PA (e.g. drones are often manufactured internationally).
Prof. Xia Zhu-Barker	University of Wisconsin-Madison *Department of Soil Science*	11/15	Strategies to increase overall NUE in fertilizer application, determining sampling size and frequency of sampling, information on nitrogen cycling and different nitrogen types.
Mr. Miguel Oliveras	USDA NRCS - *TSP Certifier, Central Region*	12/16	Discussed requirements to register our technology/business as a Technical Service Provider, alternative government aid and incentive programs available to agricultural service providers and farmers.
Prof. Raj Khosla	Kansas State University *Department of Agronomy*	12/19	Explanation of his current work in nitrogen management, including development of novel biodegradable nutrient sensors. Advised understanding of the spatiotemporal variability of agro-ecosystems, sampling methods, and adoption barriers of PA tech. Validated need for more detailed nitrogen understanding, as technology is currently outpacing science: John Deere has nozzle tech. for targeted fertilizer, but lacks the software to identify precise N needs.
		4/17	Corroborated operational approach to solving N data gaps, advised on slight system modifications to avoid plant injury.
Prof. Sheng Wang	NASA Acres, UIUC *Remote Sensing and Agroecosystem Modeling to Support Resource-Efficient Nitrogen Management in the Midwest*	4/25	Discussed the Acres project and the operational considerations of a cross-scale Nitrogen management system, particularly the data assimilation requirements and modeling challenges of integrating satellite imagery, multispectral drone data, and ground sampling to produce tailored N distribution analysis. Validated the importance of this solution in the agricultural space.

Appendix D

Cost Assessment

Table D.1: Overall Cost Breakdown for 1 System Serving 5600 Acres over one year

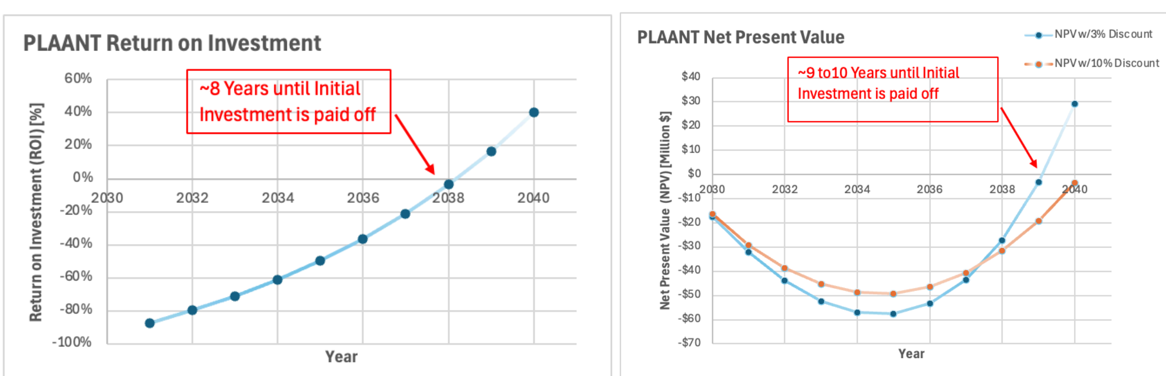
Category [$/5 yrs]:	Surveyor	Soil Sampler	Sprayer	TOTAL
RTD&E	660,000	16,500,000	660,000	17,820,000
Fixed Equipment	$435	$17,568	$26,224	$44,227
Training	$645	$6,666	$3,461	$10,772
Maintenance	$50,068	$101,333	$51,800	$203,201
Operation				$210,000
Transportation				$44,518
Total Non-Recurring Cost [$]				**17,820,000**
Total Recurring Cost [$/yr]				**$512,718**

Table D.2: Detailed Cost Breakdown for 1 System Serving 5600 Acres over one year

Category	Components	Cost/year
Equipment	Multispectral Drone (x1)[85] Spare Factor = 10% Cost of Fleet	$870/(2 yrs)
	Soil Sampling Drone (x5)[118] Unit Cost = $15,971 Spare Factor = 10% Cost of Fleet	$87,840/(5 yrs)
	Fertilizer Sprayer Drone (x6)[118] Unit Cost = $18,291 Spare Factor = 10% Cost of Fleet	$131,120/(5 yrs)
	Nitrate Test Strips Unit Cost = $0.46 / Test[88]	$138
	9-13 kW Diesel Generator[89]	$2,000/(10 yrs)
Operation	Fleet Energy Cost Non-Consumable ~ $0.15/kWh Consumable ~ $3.14/gal[90]	$74
	Drone Operators (x3) Individual Salary = $70,000[91-92]	$210,000
Maintenance	Technicians (x4) Individual Salary = $50,000[117]	$200,000
	Material & Repair Costs Surveyor ~ $70 Soil Sampler ~ $2700 Sprayer ~ $1,800	$4,535
Transportation (over 5 yrs) (assume 40% of full-time usage of shipping hauler)	Fuel (Diesel) [93] ~41,000 gal / 5 yrs → 8,000 gal/yr	$140,000 / (5 yrs)
	Truck Maintenance [93]	$30,000 / (5 yrs)
	Vehicle Insurance [93]	$32,000 / (5 yrs)
	Tire Changes [93]	$8,000 / (5 yrs)
	Truck Annual Cost [94] Unit Cost: $240,000 (20 years)	$12,000
	Operating Hours/year	1555
RTD&E (Research, Test, Development and Evaluation)	Surveyor Drone [95]	$660,000
	Soil Sampler Drone [95]	$16,500,000
	Sprayer Drone [95]	$660,000

Table D.3: Profit and Savings Calculations

Fertilizer Average Cost	
	1. Liquid Nitrogen = ($592.75 / ton)[53] 2. Ammonium Sulfate = ($517.70 / ton)[53] 3. Urea = ($709.77 / ton)[53] 4. MAP = ($1,079.12 / ton)[53] 5. (592.75 + 517.70 + 709.88 + 1079.12)/4 = $724.86 Inflation Adjustment: $724.86/ton (2015) → $978.87/ton (2024)
Nitrogen Savings Calculations	
Savings Across U.S.	1. 11.96 million metric tons used in U.S. in 2022[54] 2. 11.96 million tons * 978.87/ton = $11.71 billion of Nitrogen Fertilizer expenses in U.S. 3. $11.71 billion * 35% Nitrogen Fertilizer Savings/Reduction[54] = $4.0975 billion in N Savings across U.S. at 100% adoption 4. At 30% adoption by 2054 → $1.23 billion in N savings
Savings Per 400-Acre Farm & Per Acre	1. 1,742,000 total farms in the U.S. base on 2022[96] 2. 748,086 400-acre plots[96] (34% of total farms) are cropland farms [97] (Use this number to account for farm size variability 3. For a 400-acre farm (close to mean [98]) → $4.0975 billion/748,086 plots = $5,477 N savings for a 400-acre farm 4. $5,477/400 acres = $13.7/acre in N savings
Crop Yield Increase Calculations	
Profit Across U.S.	1. Aggregate cash generated in 2023 from corn, soybean, and cotton = ($75.8 + $56.1 + $7.1) billion = $139 billion[55] 2. Predicted 20% increase in Crop yield with precision agriculture in fertilizer application[56] 3. $139 billion * 20% = $27.8 billion increased profit for corn, soybean, cotton 4. At 30% adoption by 2054 → $8.4 billion in N savings
Profit Per 400-Acre Farm & Per Acre	1. For a 400-acre farm (close to mean [98]) → $27.8 billion/748,086 plots = $37,162 N savings for a 400-acre plot 2. $37,162/400 acres = $92.9/acre additional yield profit



(a) (b)

Figure D.1: Plot (a) shows the trend of return on investment (ROI) over 10 years since US full launch at 2030, and plot (b) shows the Net Present Value (NPV) over 10 years.[122]

Table D.4: Return on Investment (ROI) Breakdown for PLAANT based on services performed.

Category	Start Up R&D Cost	Annual Recurring Cost
Surveyor	$660,081	$125,632
Soil Sampling	$16,500,000	$219,829
Sprayer	$660,081	$161,958
(SymC) System Cost (400-acre system) [$] (This is *PLAANT's* recurring expenses)	$17,820,162	$512,567
Nitrogen Annual Savings (35% Savings) [$]		$4,097,500,000.00
Nitrogen Annual Profit Increase (+20% Yield) [$]		$27,800,000,000.00
Savings Fraction of Profit Increase		0.13
Yield Fraction of Profit Increase		0.87
Total Profit Increase (35% Savings + 20% Yield) [$]		$31,897,500,000.00
Total number of farmland acres in the U.S.[96] (cropland, rangeland, etc.)		880,100,848
Total number of 400-acre areas		2,200,252
(TF) Number of 400-acre areas that are cropland (34% of total)		748,086
Percentage of 400-acre areas controlled by mid-large scale farms		0.8
(PM) *PLAANT* Profit Margin [%]		10.0
(U) Utilization (Number of Farms to service per 400-Acre System)		14
Price of one 400-Acre Service (Annual) [$]		$36,612
Revenue per 400-Acre Service (Annual) [$]		$40,273
Profit per 400-Acre Service [$]		$4,029
(400AcreRev) 400-Acre Farm Revenue [$]		$42,639
Return on Investment (ROI) for Farmer [%]		**6.4**

Adoption Rate % *(Sigmoid Curve)*	$Adoption\ Rate\ \% = \frac{100}{1+exp(-0.2(x-2058))}$ • X = Year
PLAANT Cost (Business Expenses)	$Service\ Cost = \frac{Adoption\ Rate\ \%}{100} * \frac{TF}{U} * (SymC)$ • TF = 748,086 farms, U = 14 farms/service, 1 farm = 400 acres, SymC = $512,791.73
PLAANT Revenue (Price of 400-Acre Service)	$PLAANT\ Revenue = (Service\ Cost) * (1 + (PM/100))$ • PM = PLAANT Profit Margin of 10%
Farm Revenue	$Farm\ Revenue = \frac{Adoption\ Rate\ \%}{100} * TF * (400AcreRev)$ • 400 Acre Rev = $42,639 (from +20% Yield, 35% N Saved)
Profit	*PLAANT Profit = PLAANT Revenue - PLAANT Cost* *Farm Profit = Farm Revenue - PLAANT Revenue*
ROI Formula	*ROI = Sum of Profit since launch / (Non-Recurring Profit * years since launch)*

Table D.5: Comparison of PLAANT vs. Conventional Soil Sampling Service labor costs for 300 samples (2-4 grams each, 1 foot deep) taken over one day [116]

PLAANT Sampling Cost	
2 Technicians	72
2 Operators	50
Sampling Time [hr]	8
Overall Cost/Hr [$/hr]	122.00
Total Labor Cost of Visit [$]	976
Conventional/Manual Soil Sampling Cost	
Cost/Hour for 1 person [$/hr]	$24.00
Samples Taken after 6 hours	40
Samples/Hour	6.67
Samples after 8 hrs	53.3
Crew Size	6
Overall Cost/Hr [$/hr]	144.00
Total Labor Cost of Visit [$]	1,152
PLAANT/(Manual Labor Sampling) Cost Ratio	84.72%

Table D.6: Calculations for CO_2 Emissions for drone-tractor comparison

Category	Number	Units	CO2 Emissions	Units
Drone [71]	1	km	0.00441	kg
Tractor	5	km/h	0.035	g/s
Tractor (5 km/h)	1	km	0.0252	kg
Distance Tractor Travels (5 km/h)	1.55822899	km	0.03926737055	kg
Fertilizer Drones Distance	1.55822899	km	0.006871789847	kg
Ratio of Drone/Tractor Emissions			0.175	
Ratio of (5 Drones)/(1 Tractor) Emissions			0.875	

Appendix E

Deployment Assessment

Table E.1: Key Technology Components, Purpose, and TRL[59]

Component	TRL	Purpose
500 Wh/kg Lithium Ion Battery	4	Projections estimate current Li-ion battery technology extends to 500 Wh/kg.[40] Current commercial batteries for quadcopter drones are ~126 Wh/kg.[99]
Nitrate Test Strips	9	Nitrate strips are straightforward, long-standing tests used by farmers to determine soil sampling content, but size modifications must be made to adapt testing kits to autonomous flight vehicles.[18]
Precision Agriculture Software	9	Topography mapping and precision agriculture software for multispectral drones currently exist in the market.[32][100]
Nano Color Spectrometer	9	NanoLambda (in South Korea) has developed a cost-effective, small spectrometer.[101] Separately, research indicates that small single photon grating nanoscale spectrometers have been fully developed, but have yet to be used on flight vehicles or commercially.[102]
Auger Deployment System	6	Similar research for defense purposes has tested a drone with an auger-actuation system that allows the drone to dig holes, bury sensors in holes, and takeoff to another drilling site.[81]
Multispectral Camera	9	Numerous spectroscopy sensors, such as the Hyplant standalone sensor or the DJI Mavic 3 drone-multispectral combination are currently used on commercial farms.[62]
RTK Base Station	9	Real-Time Kinematics, such as the R26 V1 RTK base station, are currently sold commercially.[103]
Modified Quadcopter	6	Quadcopters are the current flight vehicles used for precision agriculture research.[82] Modifications will be needed to incorporate nitrate strip tests and the Edelman auger.
Sprayer Drones	9	Multirotor drones used to apply fertilizer at specific areas on the field are fully developed and commercialized.[86]

Table E.2: Federal Legislative and Program Policy Support for PLAANT UAS

Source	Policy	Purpose
H.R.2 – 115th Congress	*The Agriculture Improvement Act of 2018 (signed into Law)*	This act allows the government to fund projects that improve rural agriculture through means of better equipment housing, wifi connection, and technical support for agriculture services.[104] Benefit to System: funding to service providers to establish housing and additional research into system development.
H.R.4481 – 115th Congress	*Precision Agriculture Connectivity Act of 2018 (passed the House)*	This act aims to specifically create a task force to improve broadband mobile wifi signal across all agriculture farms in the U.S. and plans to have 95% of all U.S. farms to have reliable internet by 2025.[105] *Benefit to System:* funding to further reduce the risk of poor wireless connection and improves real-time data transmission frequency from system to base station
Natural Resource Conservation Service – USDA	*Environmental Quality Incentives Program (EQIP)*	Offers funding to encourage farmers to use technology that benefits soil health, water and air quality, and wildlife through Conservation Innovation Grants.[106] *Benefit to System:* funding to service providers to use this technology with the outcome of improving environmental impact and local habitat sustainability.
Natural Resource Conservation Service – USDA	*Conservation Stewardship Program (CSP)*	Provides annual payments of $4000 and up over 5 years to farmers who create a formal plan and contract to improve land conservation by reducing inorganic chemicals and compounds added to farmland.[107] *Benefit to System:* financial support for farmers interested in purchasing a *PLAANT* subscription to reduce excess nitrogen fertilizer added to crop fields.

Figure E.3 - Legend of Ullman Risk Assessment [108]

	Hazard Category			
	I	**II**	**III**	**IV**
Frequency of Occurrence	**Catastrophic**	**Critical**	**Marginal**	**Negligible**
A. Frequent	1	3	7	13
B. Probable	2	5	9	16
C. Occasional	4	6	11	18
D. Remote	8	10	14	19
E. Improbable	12	15	17	20

Hazard Risk Index	Criterion
1 - 5	Unacceptable
6 - 9	Undesirable
10 - 17	Acceptable with review
18 - 20	Acceptable without review

Legend: – Acceptable, – Undesirable, – Unacceptable

Table E.4: Assessed Risks and Abatement Plan through Ullman's risk assessment [108]

Risk	Description	Frequency and Severity	Abatement Action	With Abatement
a	Drilling Stress on Drone	BIII = 9	Carbon fiber wing surface, Polyether Ether Ketone landing anchors, ASTM 1060 Steel landing frame.[109] Water is stored in drone wings for additional stability.	14
b	Environmental Factors	CII = 6	Liquid ingress protection coating, even distribution of fuselage weight,[65] Quad X frame rotor placement to maintain evenly distributed lift.[110]	11
c	Data variation from flight movement	EIV = 20	Sensor mount design with damping mechanism,[111] chemical testing conducted while landed, noise filters to prevent interference.	18
d	Sensor failure	CIII = 11	Maintenance LED indicator, removable sensor mount with hooks, bolts.[111]	20
e	Auger obstruction	DII = 10	Closed-loop force/pressure feedback at the actuator, auger ejection.	19
f	Drone collision	CI = 4	Proximity and ultrasonic sensors,[112][110] Low altitude (<100 ft) flight paths for drilling drones, ~164 ft for survey drones.[62]	10
g	Battery explosion	CI = 4	Cooling fans and temperature and current monitoring.[113]	18
h	Inaccurate Data / Recommendations	CIII = 11	To prevent outliers, 15 samples will be taken over 20 acres during peak growth seasons (May-August), recommendations will be updated every 2 weeks.[114]	19
i	Landing Instability	BIII = 9	Propeller Guards, Weight of drone much larger than canopy bending moment[69], alternative design modeling the Terra-22[70]	16

Appendix F

Lift over Drag Calculations References[83-84]

1) Gross Weight Sizing Equation.

$$W_o = \frac{W_p}{\left[1 - \left(\frac{W_e}{W_o}\right) - \left(\frac{W_{ce}}{W_o}\right) - \left(\frac{W_{ne}}{W_o}\right)\right]}$$

Where;

W_o = Gross Weight, lb

W_p = Payload, lb

$\left(\frac{W_e}{W_o}\right)$ = Empty Weight Fraction, (-)

$\left(\frac{W_{ce}}{W_o}\right)$ = Consumable Energy Weight Fraction (fuel fraction), (-)

$\left(\frac{W_{ne}}{W_o}\right)$ = Non-consumable Energy Weight Fraction (battery weight fraction), (-)

Energy Weight Fraction (Breguet Equation)

Consumable: $\left(\frac{W_{ce}}{W_o}\right) = (\tau_{ce}) * \exp\left[(-1)\left(\frac{E*V}{H_f*\eta_o*\frac{L}{D}}\right)\right] = (\tau_{ce}) * \exp\left[(-1)\left(\frac{E*V*c_p}{\eta_p*\frac{L}{D}}\right)\right]$

Non-Consumable: $\left(\frac{W_{ne}}{W_o}\right) = (\tau_{ne}) * \left(\frac{E*V}{H_b*\eta_o*\frac{L}{D}}\right) = (\tau_{ne}) * \left(\frac{E*V*c_p}{H_b*\eta_p*\frac{L}{D}}\right)$

Where;

$\tau_{ce} =$ power contribution factor due to consumable energy, 0 < τ_{ce} < 1

$\tau_{ne} =$ power contribution factor due to non-consumable energy, 0 < τ_{ne} < 1 … Note: $\tau_{ce} + \tau_{ne} = 1$

$E =$ endurance, sec

$V =$ flight speed, ft/sec

$H_f =$ energy content of the consumable energy, ft

$H_b =$ energy content of the non-consumable energy, ft

$\eta_o =$ overall efficiency of the power train = $\eta_p \eta_{th}$, (-)

$\eta_p =$ propulsor efficiency = $\frac{TV}{P_s}$, (-), efficiency of converting shaft power into propulsive thrust.

$\eta_{th} =$ thermal efficiency, (-), efficiency of converting stored consumable energy into shaft power.

$c_p =$ average specific fuel consumption during the flight segment, (1/ft)

$\frac{L}{D} =$ average lift-to-drag ratio during the flight segment, (-)

Lift to Drag Ratio

$$\frac{L}{D} = \frac{L}{\left(\frac{P_{cr}}{V}\right)} \cong \frac{T}{\left(\frac{P_{cr}}{V}\right)} = \frac{V}{\left(\frac{P_{cr}}{T}\right)} = \frac{V}{\left(\frac{P_{cr}}{P_h}\right)\left(\frac{P_h}{T}\right)}, \text{(-)}$$

$$\frac{P_{cr}}{P_h} = \frac{C_{P,cr}}{C_{P,h}} = \frac{[C_{Pi}+C_{Po}+C_{Pp}]_{cr}}{[C_{Pi}+C_{Po}]_h} = \frac{\left(\frac{\kappa C_T^{3/2}}{\sqrt{2}}\left(\frac{\lambda_{cr}}{\lambda_h}\right)\right)+\left(\frac{\sigma C_{do}}{8}(1+4.6\mu^2)\right)+\left(\frac{1}{2}\left(\frac{f}{A}\right)\mu^3\right)}{\left(\frac{\kappa C_T^{3/2}}{\sqrt{2}}\right)+\left(\frac{\sigma C_{do}}{8}\right)}, \text{(-)}$$

$$\frac{P_h}{T} = V_t\,\frac{C_{p,h}}{C_T} = V_t\,\frac{\left(\frac{\kappa C_T^{3/2}}{\sqrt{2}}\right)+\left(\frac{\sigma C_{do}}{8}\right)}{C_T} = V_t\left(\frac{\kappa C_T^{1/2}}{\sqrt{2}}\right)+\left(\frac{\sigma C_{do}}{8C_T}\right), \text{(ft/sec)}$$

Where;

Subscript “cr” = cruise

Subscript “h” = hover

Subscript “i” = induced

Subscript “o” = rotor blade profile

Subscript “p” = parasite

$L = W = T\cos\alpha \sim T$, or Lift = Weight ~ Thrust, (lb)

$\alpha =$ rotor disk inclination to freestream velocity, (rad)

$P =$ Power Required, ft-lb/sec

$C_T = \frac{T}{\rho A V_t^2}$ = Thrust Coefficient, (-)

$C_P = \frac{P}{\rho A V_t^3}$ = Power Coefficient, (-)

$\rho =$ ambient density, slugs/ft^3

$A =$ Disk Area (all rotors), ft^2

$V_t =$ Tip speed of rotors, ft/sec

$\mu =$ Advance Ratio $= \frac{V\cos\alpha}{V_t} \sim \frac{V}{V_t}$, (-) … for small disk inclination angles.

$\lambda = \frac{v_i}{V_t}$ = Inflow Ratio, (-)

$\lambda_{cr} = \mu\tan\alpha + \lambda_i = \mu\tan\alpha + \frac{C_T}{2\sqrt{\mu^2+\lambda^2}} \sim \mu\tan\alpha + \frac{C_T}{2\mu}$ for μ>0.1

$\lambda_h = \frac{v_h}{V_t} = \sqrt{\frac{C_T}{2}}$ = induced velocity ratio at hover, (-)

$\sigma =$ rotor solidity, (-)

$C_{do} =$ average blade drag coefficient, (-)

$\frac{f}{A} =$ Parasite drag area to disk area ratio, (-)

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