UNIVERSITY OF PASSO FUNDO

INSTITUTE OF EXACT SCIENCES AND GEOSCIENCES

GRADUATE PROGRAM IN APPLIED COMPUTING

SAS Pro: An Integrated Mobile Tool for Strawberry Disease Control and Multifungicide Resistance Strategies

José Henrique Debastiani Andreis

Passo Fundo

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SAS PRO: AN INTEGRATED MOBILE TOOL FOR STRAWBERRY DISEASE CONTROL AND MULTIFUNGICIDE RESISTANCE STRATEGIES

José Henrique Debastiani Andreis

Thesis submitted to the University of Passo Fundo in partial fulfillment of the requirements for the degree of Master in Applied Computing.

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JOSÉ HENRIQUE DEBASTIANI ANDREIS

On the twenty-eighth day of March two thousand and eighteen, at 9:00am BRT, on the Institute of Exact Sciences and Geosciences, building B5 of the University of Passo Fundo, was hold the public defense session of the Course Final Work **"SAS Pro: An Integrated Mobile Tool for Strawberry Disease Control and Multifungicide Resistance Strategies"** authored by José Henrique Debastiani Andreis, academic of the Graduate Program in Applied Computing - PPGCA / UPF. According to information provided by the Postgraduate Council and listed in the archives of the PPGCA Secretariat, the student fulfilled the necessary requirements to submit his work to be evaluated. The examination board was composed by Dr. Clyde William Fraisse, Dr. Willingthon Pavan e Dr. Natalia Peres. After the presentation and arguing, the examining board considered the candidate APPROVED. A period of up to forty-five (45) days, according to the Rules of the PPGCA, was granted for the academic to submit the final writing to the Postgraduate Council, in order to make the necessary referrals for the issuance of Master in Applied Computing Diploma. To record, this minute was drawn up, which are signed by the members of the examination board and by the PPGCA Coordinator.

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SAS PRO: UMA FERRAMENTA MÓVEL INTEGRADA PARA CONTROLE DE DOENÇAS E ESTRATÉGIAS DE RESISTÊNCIA A FUNGICIDAS NA PRODUÇÃO DE MORANGO

RESUMO

O controle de doenças é um componente importante na produção de morango mundialmente. Existe a necessidade de uma maior eficiência no uso de agroquímicos na produção de frutas, e também de minimizar riscos de desenvolvimento de resistência em patógenos.

Neste trabalho é apresentado o desenvolvimento de uma plataforma e aplicativo móvel (SAS Pro), que integra modelos de infecção de doenças, registros de pulverização, e diretrizes de gerenciamento de resistência objetivando fornecer recomendações de controle mais específicas, assim como, reduzir o risco de desenvolvimento de resistência em patógenos, através do gerenciamento automático de restrições de uso de fungicidas por aplicação, safra, e classe química.

Palavras-Chave: agricultura, clima, doenças de plantas, resistência a fungicidas, tecnologias de informação e comunicação.

SAS PRO: AN INTEGRATED MOBILE TOOL FOR STRAWBERRY DISEASE CONTROL AND MULTIFUNGICIDE RESISTANCE STRATEGIES

ABSTRACT

Disease management is an important component in strawberry production worldwide. There has been the need for more efficient use of agrochemicals in specialty crops production, while also minimizing risks of resistance development in target pathogens.

This project presents the development of a platform and mobile application (SAS Pro), that integrates disease infection models, on-field spray reports, and fungicide resistance management guidelines aiming to provide more specific product and spraying recommendations, as well as, reduce selection for resistance on target pathogens, by automatically managing restrictions of fungicide use per application, season, and chemical class.

Keywords: agriculture, climate, fungicide resistance management, information and communication technologies, plant diseases.

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LIST OF ABBREVIATIONS

Hum. – Humidity

Prec. – Precipitation

Tbase. – Base Temperature

Temp. – Temperature

Tmax. – Maximum Temperature

Tmin. – Minimum Temperature

Solar R. – Solar Radiation

Wind S. – Wind Speed

LIST OF ACRONYMS

AD – AgroClimate Database

API – Application Programming Interface

APNS – Apple Push Notification Service

APS – Amer Phytopathological Society

AS – AgroClimate Services

AWS – Automated Weather Stations

BSON – Binary JavaScript Object Notation

CHA – Chill Hours Accumulation

EPA – Environmental Protection Agency

ERD – Entity Relationship Diagram

ETC – Crop Evapotranspiration

ETO – Evapotranspiration

ERD – Entity Relationship Diagram

FAO – Food and Agriculture Organization

FAWN – Florida Automated Weather Network

FC – Field Capacity

FQPA – Food Quality Protection Act

FRAC – Fungicide Resistance Action Commitee

FSREF – Florida Strawberry Research and Education Foundation

GCM – Google Cloud Messaging

GDD – Growing Degree Days

HTTP – Hypertext Transfer Protocol

ICT – Information and Communication Technologies

IPM – Integrated Pest and Disease Management

JSON – JavaScript Object Notation

KC – Crop Coefficient

LWD – Leaf Wetness Duration

MOA – Mode of Action

M2M – Machine to Machine

NPM – Node Package Manager

MVC – Model View Controller

NWS – National Weather Service

ODM – Object Data Mapping

PFD – Postbloom Fruit Drop

REST – Representational State Transfer

RMG – Resistance Management Guidelines

SAS – Strawberry Advisory System

SDK – Software Development Kit

SQL – Structured Query Language

SRDT – Spray Recommendation Decision Tree

SWB – Soil Water Balance

SWHC – Soil Water Holding Capacity

UF – University of Florida

WDSS – Weather Data Source Server

WP – Wilting Point

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1. INTRODUCTION

The development of resistance in some pathogens to classes of fungicides is a major concern in strawberry production [1]. This issue can be aggravated when resistance management guidelines (RMG) are neglected or incorrect followed.

RMG comprise important directives for the maintenance of fungicides efficacy on the control of diseases. Warm and humid climates are associated with increased risk of resistance development due to the higher occurrence of fungi-based diseases and consequently higher number of fungicide applications per season.

Weather-based disease infection models provide an effective way of reducing fungicide use, and consequently minimize risks of resistance development. Despite the significant adoption of disease alert tools by strawberry producers, concepts of resistance management can be difficult to follow due to the great number of chemical classes, active ingredients, dosage and application thresholds involved. Restrictions of use such as maximum number of applications per season are generally provided on product labels but growers might not be aware that these restrictions should be considered for the entire chemical class and not only for a specific product. Discrepancies between RMG and product labels can lead to misinformed actions on disease control practices, what can aggravate risk of resistance development.

Meteorological conditions should be considered before and during spraying of agrochemicals to avoid off-target deposition. Besides causing inefficiency on disease and pest control, spray drift contributes to the emission of hazardous substances in the environment, which has been a prevailing topic on food and ecological safety regulations worldwide. Relative humidity, temperature and wind speed are the basic meteorological and atmospheric conditions associated with spray drift. Guidance to avoid spray drift are now given in most of agrochemicals labels worldwide [2], but can be difficult to be followed considering the lack of real-time and forecasted weather conditions.

Colletotrichum acutatum and *Botrytis cinerea* are the causal agents of Anthracnose and Gray Mold, the two main diseases affecting strawberry production worldwide. The spraying of fungicides to control these diseases are necessary throughout the production cycle and represent approximately 15% of total operational costs [3]. *Botrytis cinerea* is also considered a high risk pathogen for fungicide resistance development and it is often the first pathogen to develop resistance to any new chemical classes. The economic importance of these pathogens and influence in strawberry production make an ideal model to study fungicide resistance management practices, which can later be implemented in other commodities.

Anthracnose and Botrytis fruit rot have been an important study subject of researchers at University of Florida (UF) and contributing institutions. As result of these research efforts, the Strawberry Advisory System (SAS) [4] was created and is currently in use in southeastern USA. SAS provides disease infection risks and fungicide spraying recommendations for Anthracnose and Botrytis fruit rot in supported regions, with significant adoption among strawberry producers SAS features and infection models served as foundation for the development of SAS Pro. The main objective of this project was to develop a platform comprising a generic database and model for fungicide application recommendations based on Integrated Pest and Disease Management (IPM) principles.

The integration of existing Anthracnose and Botrytis disease infection models to user-input spraying reports provide more specific and automated recommendations. The developed mobile tool for iOS and Android operating systems provides disease risk assessment, spray recommendations, and resistance management guidelines.

By making use of user-input spray reports to address when and what products were applied in a particular field, as well as restrictions on fungicide use, for a more suitable product recommendation, SAS Pro helps growers to avoid practices that are known for increasing resistance in pathogens such as consecutive spraying of products with a specific mode of action and formulation, providing enhanced efficiency on fungicide use.

2. LITERATURE REVIEW

2.1 INTRODUCTION TO WEATHER-BASED DECISION SUPPORT TOOLS IN AGRICULTURE

Several areas of agriculture benefit from weather monitoring. From crop and irrigation management to disease control and planting strategies, weather-based recommendations tools have been applied in several production areas of the world for both operational and planning aspects in crop production cycles. In agriculture, meteorological and climate data can be used to quantify soil dryness [5], plant water needs [6, 7, 8] and disease infection indexes [4, 3, 9].

Table 1 represents meteorological recommendation areas and corresponding required weather parameters. Some parameters are not generally available from environmental measurements but can be easily estimated using basic variables like temperature for growing degree days (GDD) and chill hours accumulation (CHA), or through specific models as it is the case for reference evapotranspiration (ETo) and leaf wetness duration [1] (LWD) estimation.

Table 1. Agriculture recommendation areas and required weather parameters.

AREA	TEMP.	HUM.	PREC.	WIND S.	WIND D.	SOLAR R.	ETo	LWD.	GDD.	CHA.
Drought Indexes.	X	X	X	X		X	X			
Irrigation Management.	X	X	X	X		X	X			
Disease Risk	X	X	X					X		
Crop Development	X	X	X			X			X	X
Disease/Pest Control	X	X	X	X	X					

Crop development, water management, and disease control are different study areas of a same system. The integration of such tools corresponds to better results on each of the implemented models.

- **Crop development, planting strategies and climate risk:**

  Historical meteorological data can be used to assess best sowing periods [10, 11], climate variability, and as inputs to a variety of crop development models for specific commodities and regions. As described by Fraisse, seasonal climate variability is a major source of production risks [12], being conditions of lack or excess of water the major causes for crop losses in the Unites States [13]. Production risks can be reduced through the use of climate forecasts, especially considering its accuracy and producers flexibility to adapt farming operations to it [12].

  The capacity to adapt plays an important role to minimize the severity of climate variability impacts in food production. Easier adaptations such as switching planting dates or selecting a different crop variety can minimize negative impacts, while more costly measures like development of new

[1] Leaf wetness duration is defined as a unit of time on which a leaf surface is subject to moisture, derived from dew or precipitation.

crop varieties and investments in irrigation are more prone to yield better results in a changing climate.

Growing degree days (GDD) and chill Hours accumulation (CHA) are the simplest variables commonly used to estimate plant development and phenological stages [2] changes on both row crop and fruit production. While they do not provide the improved accuracy found on more complex crop development models, they can be extremely useful on plant development estimation and on-field operational decisions.

GDD are used to relate plant growth, development and maturity to air temperature [14]. Equation 1 presents the method used for daily estimation of GDD, where Tbase represents a base temperature on which a determined plant or variety is best adapted to develop and grow [14].

$$GDD = \frac{Tmax + Tmin}{2} - Tbase \tag{1}$$

Chill hours accumulation (CHA) is generally used in fruit production and represents the number of hours on which temperatures stayed below or between a certain threshold, these accumulated values are expressed as chill units. Chill units can be used to determine when a fruit-bearing tree will develop leaves and blossom. Different species of plants have different chilling requirements to reach specific vegetative and reproductions phases. Two ranges of temperature are commonly used to estimate accumulated chill hours [15]:

1. Number of hours with air temperature below 7°C.
2. Number of hours with air temperature between 7°C and 0°C.

- **Soil water balance:**

  Irrigation scheduling tools often make use of soil water balance (SWB) models. SWB models are generally a function of reference evapotranspiration, soil characteristics, crop coefficients, irrigation and precipitation inputs.

  As described by Irmak and Haman [16], evapotranspiration is a combined process of both evaporation from soil and plant surfaces and transpiration through plant canopies. In the evapotranspiration process, the water is transferred from the soil and plant surfaces into the atmosphere in the form of water vapor.

  Reference evapotranspiration (ETo) is defined as the rate of evapotranspiration from a hypothetical reference crop, generally parameters of a short green grass area are used, without considering water stress and diseases.

  The estimation of the actual crop evapotranspiration (ETc) requires applying the proper crop coefficients (Kc). Crop coefficients tend to vary depending on the current phenological phase of the plant. ETc makes possible to address a specific crop soil water losses over a period of time

[2]Phenological stages refers to periodic biological development, such as leaf emergence, flowering, and maturation, in relation to climate conditions.

and location. With additional information such as soil water holding capacity (SWHC)[3], irrigation applied and rain observed, a soil water balance model can be implemented and used for irrigation scheduling purposes.

Penman-Monteith FAO-56 [17] is largely adopted and recommended as standard method for ETo estimation given the availability of its input requirements. Table 2 presents the required parameters and units for daily ETo estimation using Penman-Monteith FAO-56 method.

Table 2. Penman-Monteth FAO-56 required inputs.

SYMBOL	PARAMETER	UNIT
Tmax	Maximum temperature	°C
Tmin	Minimum temperature	°C
RHmin	Minimum relative humidity	%
RHmax	Maximum relative humidity	%
WS	Average wind speed	ms
SR	Average solar radiation	MJ/m
P	Atmospheric pressure	kPa
A	Site elevation above sea level	m
L	Site latitude	°
D	Julian day	-

- **Disease control:**

  Disease control in agriculture is a important part of several commodities management and operational costs, responsible for 15.8 billion in chemical expenditures in United States in 2014 [18]. To avoid losses caused by a variety of pathogens, producers generally follow a fixed spraying schedule where the spraying of pesticides may occur even when there is no risk in that period and environmental conditions.

  Weather-based decision support tools are great allies on disease control in agriculture. These tools allow producers to be more efficient in their disease control strategies by alerting them when there are conditions for a specific pathogen to develop and only then recommend fungicide applications. This approach can reduce significantly the number of spraying in the field and consequently, production costs.

  Weather parameters such as temperature, humidity and leaf wetness duration (LWD) have been used as input to disease infection models in several commodities and production areas [19, 3, 20, 21].

2.2 DISEASE CONTROL IN STRAWBERRY PRODUCTION

Diseases are an important limiting factor in strawberry production. Fruit rot diseases represent the biggest threat and harvest losses. Operational actions such as variety selection, use of certified

[3]Water retained between total soil field capacity (FC), subject to drainage, and permanent wilting point (WP).

plant stock, replacement of plants between seasons, pest and weed management contribute in the control of leaf and fruit rot diseases [22].

Along direct and indirect operational efforts, the use of fungicide are usually necessary throughout the production cycle, specially in warm and humid climates where occurrence of fungi-based diseases are more pronounced.

2.2.1 Strawberry Diseases

Among the diseases affecting strawberry production, Anthracnose and Botrytis fruit rot are the main concern in different regions of the world [23]. Even on well-managed fields, losses caused by fruit rot can exceed 50% when conditions to disease development exist [24]. Fungicide applications to control these diseases represent about 15% of total operational costs [3].

2.2.1.1 Gray Mold *Botrytis cinerea*

Botrytis cinerea is the causal agent of gray mold in several species of fruits and vegetables, it is responsible for great part of pre and post harvest losses in strawberry [25] driving fungicide applications in most of small fruits production [26]. Gray mold is most damaging to strawberries during periods of prolonged wet weather during bloom and fruit development [22].

Building of fungicide resistance is a major concern with *Botrytis cinerea*. It is considered a high risk pathogen[4] for resistance development [27] and generally is the first plant pathogen to develop resistance to any class of chemicals.

Botrytis development is reported to occur with 4 hours or more of leaf wetness duration (LWD) and temperatures ranging form 15 and 22°C [4]. Figure 1 presents gray mold symptoms in a variety of fruits.

Figure 1. Gray mold symptoms in grape, raspberry, blackberry (source: Schnabel, S.J.) and strawberry (source: Peres, N.A.) (from left to right).

[4] A disease-inducing agent, such as viruses, bacteria, fungus, or other microorganisms.

2.2.1.2 Anthracnose
Colletotrichum acutatum

Anthracnose fruit rot, caused by the fungus *Colletotrichum acutatum* is a very destructive disease to certain strawberry varieties on wet and warm weather. It has been reported to cause 60-75% fruit loss [22].

Anthracnose infections can happen at any development stage and affects both ripe and unripe fruits. Control is very difficult when environmental conditions are appropriate for disease development. Thus, as described by Turechek, measures to minimize Anthracnose occurrences should start at planting, with the selection of Anthracnose-free plants [28].

Favorable conditions for Anthracnose development occur when leaf wetness duration (LWD) is higher than 13 hours and temperature is between 25 and 30°C [29]. Figure 2 displays symptoms of Anthracnose in strawberry flowers and fruits.

Figure 2. Symptoms of anthracnose in strawberry flowers and fruits (source: APS - Digital Image Collection) [28].

2.2.2 Strawberry Advisory System (SAS)

The Strawberry Advisory System (SAS) is a disease-warning tool currently in use in the states of Florida, Georgia, South Carolina, Oregon and California USA. SAS is part of AgroClimate, a web-based climate and weather information and decision support platform aiming to help agricultural producers minimize risks related to climate variability in Southeastern United States [12].

SAS monitors temperature and leaf wetness duration to automatically estimate Antrachnose and Botrytis infection indexes. Antrachnose and Botrytis fruit rot are caused by the fungus *Colletotrichum acutatum* and *Botrytis cinerea* respectively, two important pathogens in strawberry production that can cause harvest losses exceeding 50%, when conditions for disease development are appropriate [24]. The system warns producers via text messages or email when the environmental conditions measured by an automated weather station near to their fields indicate a risk of infection. Producers can then access the SAS web tool [4] or mobile app [30] to check what are the products and spraying recommendations.

Besides monitoring weather parameters to deliver real-time disease infection risk alerts, SAS also provides forecast-based infection risks, where wetness is considered when relative humidity is bigger than 95% [4]. The whole system architecture is described in the interaction diagram of Figure 3 presented below.

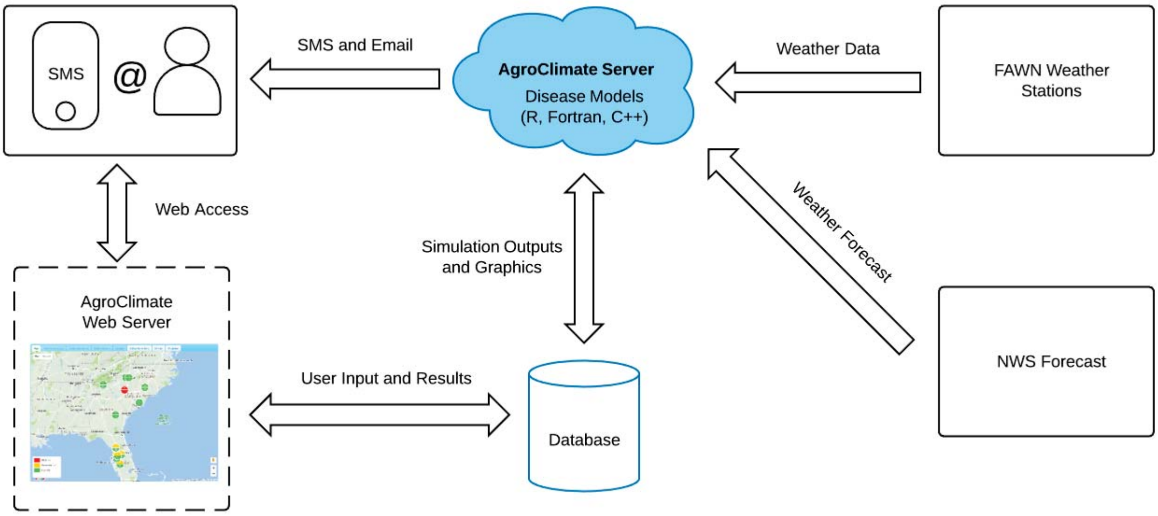


Figure 3. Strawberry Advisory System (SAS) interaction diagram. Adapted from Pavan Et al. [4]

Weather data from Florida Automated Weather Network (FAWN) is used to run Anthracnose and Botrytis infection models and send alerts to registered users if conditions for disease development are observed. A two-day disease infection index forecast is also provided within the tool. Short-term forecast weather data is obtained from the National Weather Service (NWS).

Figure 4 presents the main screen of SAS web tool. By using a map-based view users can visualize disease infection risks on several locations and weather stations included in the system. Infection risks are represented by colors and letters, where letters A and B stand for Anthranose and Botrytis respectively. Green is used to indicate "Low Risk" of infection, yellow indicates "Moderate Risk", and Red represents a "High Risk" of infection.

By selecting a weather station in the map, details about the infection risks on that location are presented. Users can click the "Recommendation" button to answer a small questionnaire where information regarding last sprayed product, presence of symptoms, and current plant development stage are used to generate spray and product recommendations (Figure 5).

With a particular station selected, users can access the "Disease Simulation" tab where graphs illustrating the simulated infection indexes for the last 30 days for Anthracnose and Botrytis are presented (Figure 6). The dashed line on the graphs represent a two-day disease infection index forecast.

By following the recommendations generated by SAS, producers have been able to reduce fungicide applications in 50% in production seasons where environmental conditions were unfavorable for disease development [4]. SAS is available online at http://agroclimate.org/tools/strawberry.

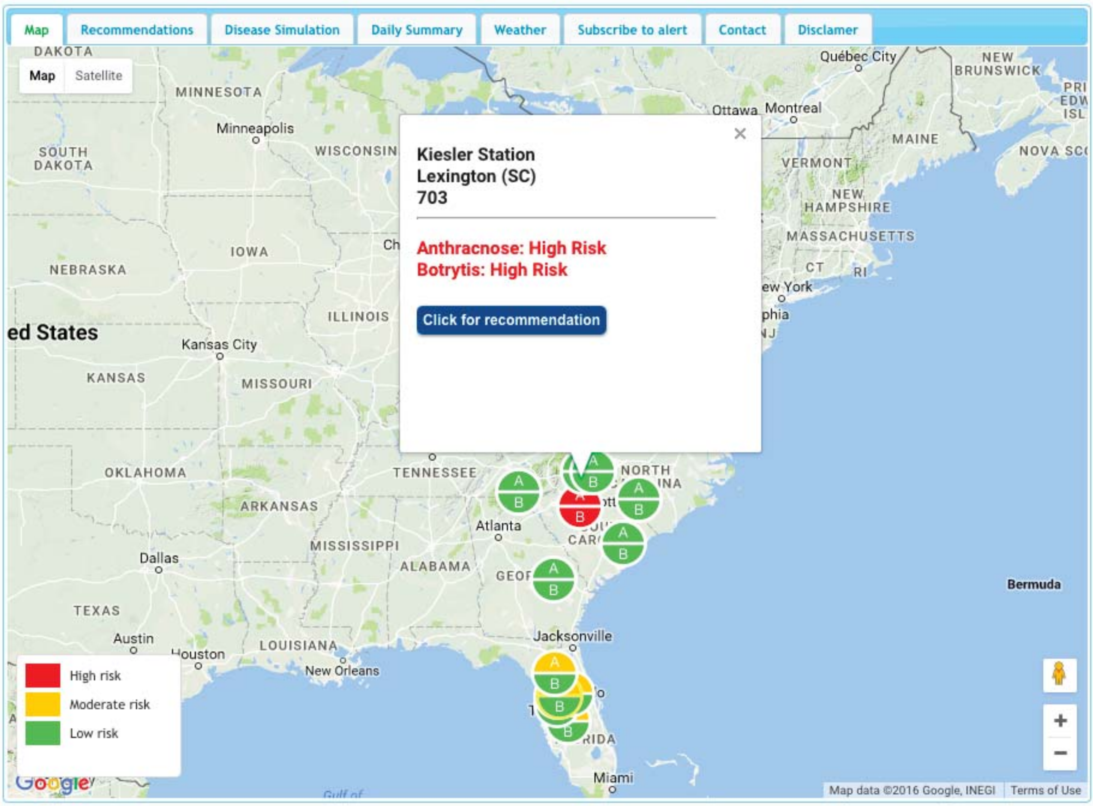


Figure 4. Strawberry Advisory System (SAS): Main screen, disease risk on supported locations [4].

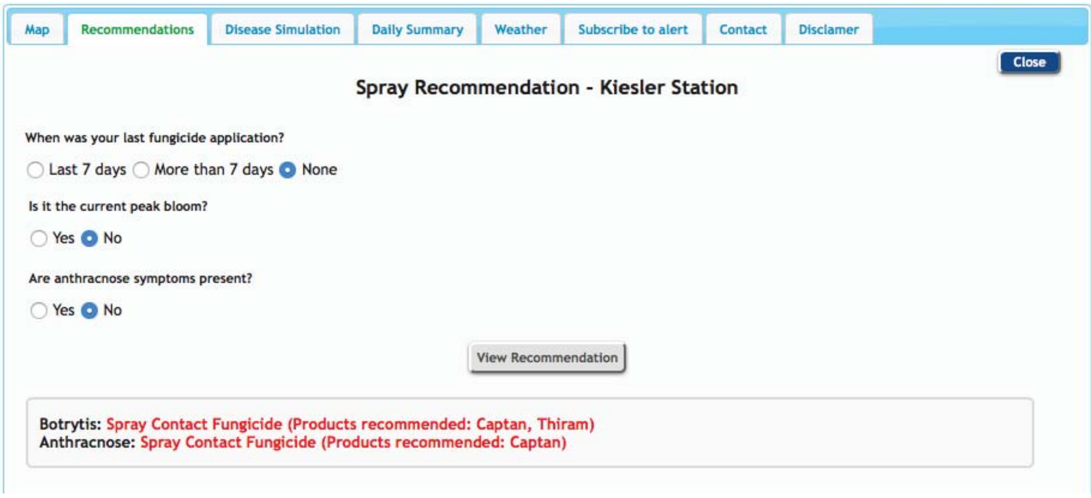


Figure 5. Strawberry Advisory System (SAS): Questionnaire and spray recommendations [4].

2.2.3 Fungicide Resistance Management

Fungicides are important tools on disease control in several commodities, acting as a barrier to protect plants from infectious pathogens. Considering they protective nature, fungicides need to be applied on a sufficient spray volume and coverage area. Reapplication of fungicides in a production cycle is common since their concentration can degrade with time and environmental conditions [31].

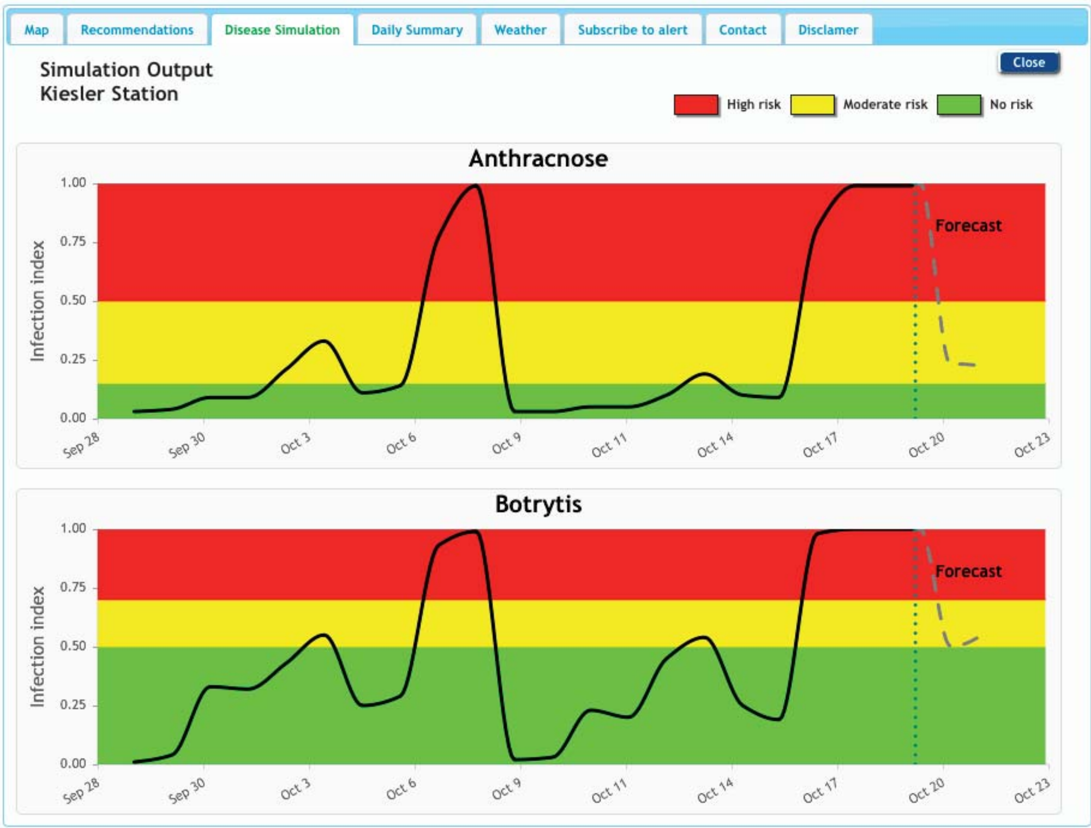


Figure 6. Strawberry Advisory System (SAS): Disease simulation and forecasted infection index [4].

Inefficient disease control can result from weathering, insufficient coverage, incorrect application rates, poor efficacy of applied fungicide on the target pathogen, and fungicide resistance. Fungicide resistance results from a complex interaction between fungicide mode of action, fungus biology, frequency of fungicide use, application rates, and cropping system [31].

Fungicide resistance is defined by a genetic adjustment or mutation, causing the pathogen to become less sensitive to a specific fungicide compost. This can be caused by a single or multiple genes adaptation. Thus, single site action fungicides[5] tend to present higher susceptibility to pathogens resistance since a mutation on only one gene of the target pathogen will cause the fungicide to become inefficient. A problem with resistance generally occurs when most of the pathogen population carries the mutated genes [31].

Integrated Pest and Disease Management (IPM) principles are used by many high quality crop producers. The use of synthetic pesticides is an important aspect of IPM and also a big concern due to its potential negative impacts in the environment. Thus, IPM recommends application of fungicide only when their use becomes necessary [32].

The Food Quality Protection Act (FQPA) from 1996 formalized the U.S. Environmental Protection Agency's (EPA) Reduced-Risk Pesticide Program. Reduced-Risk Pesticides are classified as less risky to human health and the environment with generally lower use rates and compatibility with IPM

[5]Single site action fungicides are active against only one point in one metabolic pathway in a fungus or against a single critical enzyme or protein needed by the fungus.

practices [33]. However, frequent use of reduced-risk pesticides leads to selection for resistance in the target organisms, thus the integration of resistance management guidelines in a disease alert model can help reduce even more the number of applications in the season by minimizing the development of resistance.

2.2.3.1 Fungicide Mobility and Groups

Fungicide mobility can be classified in two basic groups: Contact and Systemic. Contact fungicides remain in the plant surface having a protectant-only characteristic and should be used prior to fungal infections. Penetrant fungicides are absorbed into the plant after being applied to its surface. Because of the absorption into the plant, penetrant fungicides are considered systemic[6] fungicides with different degrees of penetration:

(a) **Locally/translaminar**: Droplets of fungicide are absorbed by plant tissue. New leaves and areas where droplets did not reach are not protected.

(b) **Acropetal (xylem-mobile)**: Droplets are absorbed by plant tissue and moves up in the xylem[7] to edge of leaves and new growth. Leaves produced after application may be protected.

(c) **Amphimobile**: Droplets are absorbed by plant tissue and moves upward and downward the plant through its xylem and phloem[8]. Leaves produced after application may be protected.

Generally, penetrant fungicides will only reduce or stop symptoms development when applied within 24-72 hours after infection [34]. Therefore a preventative approach is also recommended for penetrant fungicides.

Regardless of mobility type, fungicides efficacy will be limited when applied after symptom development and pathogen reproduction but can still slow or eliminate symptom development. Applying fungicides before pathogen symptoms are present generally results in best control [31].

Table 3 below presents a comparison of main characteristics and differences between contact and penetrant fungicides.

Table 3. Comparison of contact and penetrant fungicides [34]

CONTACT	PENETRANT
Must be applied before infection	Applied soon after infection
Prevents spore germination	Ineffective after fungus reproduction
No effect after infection	Limited curative effect
Low risk for resistance development	High risk for resistance development

[6]Systemic fungicides are absorbed into plant tissue and may offer some after-infection activity.

[7]A compound tissue in vascular plants that helps provide support and that conducts water and nutrients upward from the roots.

[8]Part of a vascular bundle forming the food-conducting tissue of a plant.

The Fungicide Resistance Action Committee (FRAC) has the mission of providing fungicide resistance management guidelines to prolong the efficacy of fungicides, limiting crop losses caused by resistant pathogens.

FRAC developed a code, with the intent to classify fungicides into groups according to their mode of action. The alternate use of products in different FRAC code[9] groups is considered an easy operational practice to manage fungicide development [34]. Guidelines from FRAC include:

1. **To not use any product exclusively**: Products of different chemical classes should be rotated or mixed;

2. **Restrict the number of treatments applied per season, and apply only when strictly necessary. Use other fungicides both beforehand and afterwards**;

3. **Maintain manufacturer's recommended dose**:

4. **Avoid eradicant use**: Avoid exposure of single site fungicides to sporulating lesions;

5. **Integrated Disease Management**: Use other means to reduce infection pressure;

6. **Chemical diversity**: Integrate many different chemicals into a spray program.

Attachment A[10] [35], presents a list of fungicides used on control of Anthracnose and Botrytis fruit rot in strawberry production. The list correlates brand name and active ingredients, grouping products by target pathogen and FRAC code. Restrictions of rate per application and season, minimum days for field reentry and harvest, and maximum consecutive and total applications per season, are provided.

2.3 AGROCHEMICAL SPRAY DRIFT

Agrochemical is a term used for chemical products used in agriculture and it refers to a broad range or pesticides, including insecticides, herbicides, fungicides, rodenticides, bactericides and others, as to synthetic fertilizers, hormones and other plant growth agents.

Given the set of chemicals largely used in agriculture and crop management, pesticides are a big concern due to its potential toxicity to humans and other species of animals and plants [36]. The potential negative impact of pesticides on human health and the environment has been prevailing topic on food and ecological safety regulations worldwide.

[9]FRAC code (fungicide group): Used to distinguish the fungicide mode of action. All fungicides within the same group (with same number or letter) indicate same active ingredient or similar mode of action. This information must be considered for the fungicide resistance management decisions. Source: FRAC Code List 2013; http://www.frac.info/ (FRAC = Fungicide Resistance Action Committee).

[10]Information provided in this table applies only to Florida, USA. Be sure to read a current product label before applying any chemical. The use of brand names and any mention or listing of commercial products or services in the publication does not imply endorsement by the University of Florida Cooperative Extension Service nor discrimination against similar products or services not mentioned.

In most countries, pesticides must be registered with a specific state agency responsible for the approval of its sale, distribution and use [36]. Applying agrochemicals in the field is an activity that requires technical expertise and operational precautions. Some pesticide products are restricted to handling by applicators with specific training on use of the product in a manner that no harm will occur to man or environment.

Factors that affect spray drift include weather [37, 38], physical properties of spray solution [39, 40] and the spray application characteristics itself, like droplet size and release high.

Adverse meteorological conditions are the biggest cause of excessive spray drift during pulverization [41]. Besides causing inefficiency on disease and pest control, spray drift contributes to the emission of hazardous substances in the environment and it is a prevailing topic on food and ecological safety regulations worldwide.

Along with droplet size and release height, meteorology plays an important role in determining the movement of spray droplets in the atmosphere as well as where these droplets land [42]. As described by Thistle [2], droplets size is critical since for smaller sizes, the effect of gravity is diminished and the effect of wind speed is increased. As also, higher release setups will make droplets spend more time in the atmosphere and wind will have more time to displace them laterally, away from the target.

Wind speed is a critical factor on agrochemical spray drift [43]. The interaction of meteorological variables such as humidity and vertical temperature structure with airborne droplets is less well understood [2] but should also be considered during applications.

Wind direction is not related to the amount of drift from an application, but it should be considered if there is the need to prevent drift to a specific location, in this case wind direction is a critical variable as the direction of air movement determines the direction in which material will drift. The fluctuation in wind direction can also be used as an indicator of the amount of atmospheric turbulence and, therefore, the amount of dilution of a cloud of fine droplets [2].

Wind speed thresholds and guidance are now given on many agrochemicals labels worldwide. Generally, wind speed at application will be limited by label restrictions of 4.5 ms^{-1}. It has been proposed that low wind speed thresholds should be advised as it is a characteristic associated with atmospheric inversions[11] [2].

The main influence of humidity in spray drift is caused by the droplet size reduction through evaporation, thus reducing the droplet velocity and increasing the influence of ambient wind speed. Evaporation rate is increased on high temperature or dry climates [2].

Evaporation has greater effect in small droplets than in larger drops because the small droplets have greater surface area relative to their volume [44]. Because of enhanced drift potential caused by higher evaporation rates, it is recommended to spray on lower temperature and humidity conditions [44].

[11] Atmospheric inversions are characterized by increasing temperatures with height.

2.4 INFORMATION AND COMMUNICATION TECHNOLOGIES IN AGRICULTURE

Information and communication have always been essential in agriculture [32]. Since the early days producers communicate to share information on planting strategies, operational practices, and risk assessment with each other. Considering the current global food production challenges, Information and Communications Technologies (ICT) bring great opportunities on increasing food production while minimizing risks related to climate variability.

The ability of ICTs on bringing new opportunities in precision agriculture and related areas is even more prominent when considered the increasing investments in research and the growing interest of private companies in the sector.

ICT decision support systems based on real-time data readings from sensors can provide critical information in all aspects of agricultural production on a level and granularity not previously possible [45], being an important aspect of Smart Agriculture implementations.

Smart Agriculture or Smart Farming refers to a bigger concept of precision agriculture where all components of a production facility are connected and context-aware. The use of physical sensors and identifiers provide the base for such connectivity, while cloud computing and services bring the support for the uniformization of data access and storage between devices. Figure 7 shows technologies involved on Smart Farming implementations.

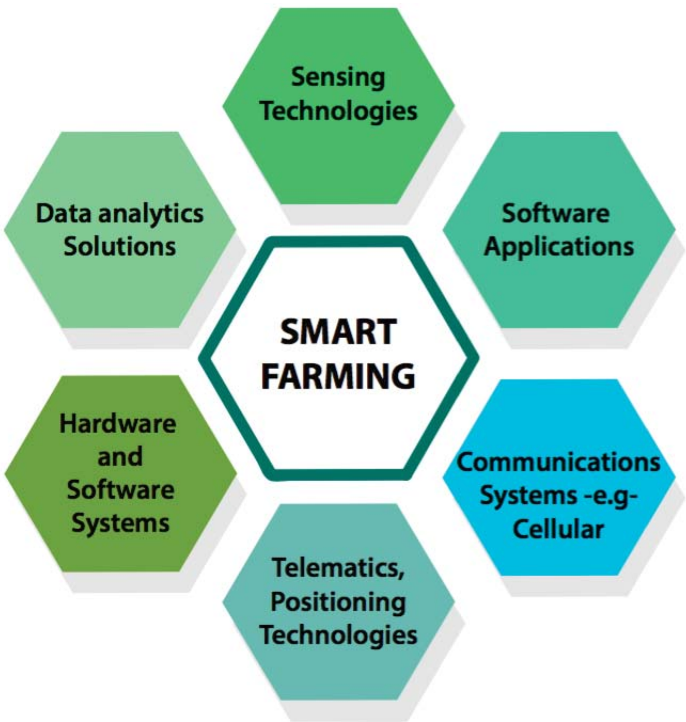


Figure 7. Technologies involved in Smart Farming implementations [45].

Several factors contribute to Smart Farming implementations, as well, a big range of stakeholders can be identified as end users of resulting products.

Technology is an important component in Smart Farming and it includes providers of wireless connectivity, sensors, M2M (Machine to machine) solutions, decision support systems, data analysis systems, geomapping and smartphone applications.

It is possible to identify a diverse range of stakeholders that have interest on real-time readily available decision support tools in agriculture. From technical workers and specialists, farm owners, farming associations, cooperatives, extension agents and research institutions, to chemical companies, financing institutions, food retailers and industry. Institutions that set market prices, consumers, and economy entities have also a major influence on how and why Smart Farming implementations are considered.

2.4.1 Mobile apps in agriculture

Mobile phones are considered an effective way to reach farmers due to its ability of aiding decisions made in the field [46]. The recent increase on use of internet-enabled devices [6, 47] brings great opportunities for the development of mobile decision support tools.

Researchers and private companies have been developing and distributing apps targeted for use in different operational and strategical aspects of food production. Migliaccio Et al. and Vellidis Et al. have developed smartphone apps for irrigation scheduling support in several commodities and regions in southeastern USA [6, 7, 8]. The developed apps are part of Smartirrigation project available at http://smartirrigationapps.org and feature the integration of soil water balance (SWB) models, observed and forecasted weather data, and crop development estimation to aid producers to be more efficient in their water use.

A weather and climate risk monitoring app was developed by Fraisse Et al. supporting iOS and Android operating systems [46]. The AgroClimate mobile app provides weather and climate reports from automated weather stations. Users can also register fields within the app and monitor weather conditions such as accumulated rain, mean temperature and drought indexes throughout the crop season. The app can be used for plant development estimation using the provided growing degree days (GDD) and chill hours accumulation (CHA). AgroClimate app also accounts for extreme weather events observed in a specific region, with information regarding number of days with temperature and rainfall above critical thresholds that can contribute to harvest losses.

Smartphones and tablets, offer bigger flexibility and are more easily accessible than conventional desktop computers [6]. Applications developed for mobile platforms can make use of novelty mobile-specific mechanisms to engage users, such as push notifications. These combined aspects provide opportune appliance of such technologies in agricultural decision support tools, specially considering the on-site, real-time nature on which operational farming decisions are made.

3. SAS PRO (STRAWBERRY ADVISORY SYSTEM)

The SAS Pro system was developed with the intent to provide an integration between disease infection models, fungicide application reports, and resistance management guidelines. The entirety of SAS Pro disease alert and fungicide recommendation system consists of three basic foundations, described below:

- **Automated Weather Stations (AWS)**: Public and private AWS are supported in the system and provide environmental readings, which then are used to estimate disease infections risks for the supported diseases: Anthracnose and Botrytis.
- **AgroClimate Services (AS)**: Responsible for processing and storing observed weather data as to run specific models to estimate disease infection indexes of a particular location and observed environmental conditions.
- **SAS Pro Mobile App**: SAS Pro manages inputs and server requests to present disease risks, as well as, spray recommendations to users.

Figure 8 presents an interaction diagram covering all aspects of the system an its prevailing process sequence. Weather data is collected by Automated Weather Stations (AWS) which are then gathered and processed by the AgroClimate Services (AS). User requests and data visualization are handled on the client mobile app. All reference and generated data is stored on the AgroClimate Database (AD).

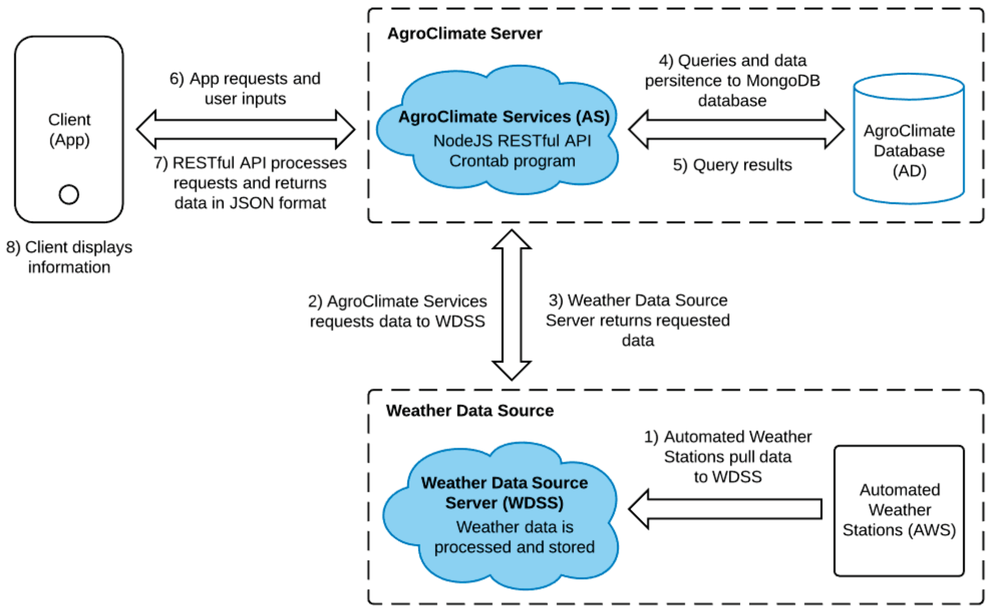


Figure 8. SAS Pro interaction diagram including client, database and services architecture. The weather data component serves as base for infection risks and recommendations generated by the AgroClimate Services (AS). The client mobile app provides user interaction and data visualization.

3.1 WEATHER DATA, WEB SERVICES, AND MODELS

Weather data from regional weather monitoring networks provide data to disease infection models. From the broader set of parameters measured by the supported weather stations, temperature and leaf wetness duration (LWD) are used to generate disease infection indexes for Anthracnose and Botrytis, which provide the foundation for the development of SAS Pro. National Weather Service (NWS) is the source of forecast weather data used to estimate disease risks for the next days in the supported regions of USA along with spray conditions analysis.

3.1.1 Web Services

AgroClimate Services process and store weather data on AgroClimate Database. A Crontab[12] program is used to schedule weather data download from the supported sources, as well as, execution of the models and storage of results.

AgroClimate Services are based on a RESTful API[13] (Application Programming Interface) architecture and are currently being used by other tools of AgroClimate platform. The services comprise operational features such as user authentication and field registration to agro-meteorological components like weather data processing and derived calculations. Node JS server-side JavaScript environment is used as base of AgroClimate Services API.

3.1.1.1 NodeJS

NodeJS allows the execution of JavaScript codes on server environment. It is based on Google Chrome's Engine V8[14] and comprises an event-driven asynchronous architecture. Support to new functionalities and development frameworks, such as database connection engines like Mongoose [49], and REST API middlewares like Restify, can be aggregated to a NodeJS program using the Node Package Manager (NPM) [50]).

Mongoose package was used for mapping of MongoDB documents to JavaScript objects, following an Object Data Mapping (ODM) structure, while the Restify[15] framework is used as an interface for HTTP protocol methods calls (GET, POST, PUT, and DELETE), providing a RESTful service architecture to manage view-controllers methods and data transfer on a client-server environment.

[12] Unix-based utility that allows tasks to be scheduled and automatically run in the background at regular intervals.
[13] Set of routines and programming standards used to access functionalities of a web platform [48].
[14] https://developers.google.com/v8
[15] http://restify.com

3.1.2 Database

A database structure was created to correlate fungicide products by brand name, active ingredients, FRAC code, restrictions of use, and environmental spraying thresholds. Spraying reports are also supported in the new SAS Pro database, where information entered by producers through the mobile apps is persisted and serve as input in other aspects of the tool. These new services and database structure are responsible of integrating fungicide recommendations and resistance management guidelines, main objective of this project.

3.1.2.1 MongoDB

MongoDB [51] is the foundation of AgroClimate Storage Services. Being a NoSQL (Not Only SQL) database, MongoDB stores data in documents with BSON format, a JSON variant. MongoDB is currently being used on the AgroClimate platform for its known flexibility and capability to scale, important aspects when non-conventional structures are considered. Which is the case of most of scientific to operational products provided by AgroClimate.

3.2 MODULES

To achieve the goal of this project, several existing modules of AgroClimate Services were expanded and new ones created (Table 4) to support features contemplating the integration of disease infection models and fungicide resistance management. These key features are directly linked to three main modules, Agrochemicals, Disease, and Season, described in the following sections and represented on the logic entity relationship diagram (ERD) of Figure 9. The cardinality and modality between documents and sub-documents are represented using Crow's Foot notation [52].

Table 4. AgroClimate System Modules.

MODULE	ITEMS
Agrochemicals	Active ingredients, Fungicide Group (FRAC, MOA...), Dose, Disease, and Restrictions
Disease	Pathogens, Models, Coefficients, and Thresholds.
Geo	Location, Country, State, County, and City.
Land Unit	Farm, Field, Area (GeoJSON), and Soil Texture.
Plant	Commodities, Varieties, and Phenological Stages.
Season	Crop Development, Activities, Events, Disease Simulations, and Recommendations.
Social	User, Organizations, and Notifications.
Weather Data	Weather data from automated stations and other sources.

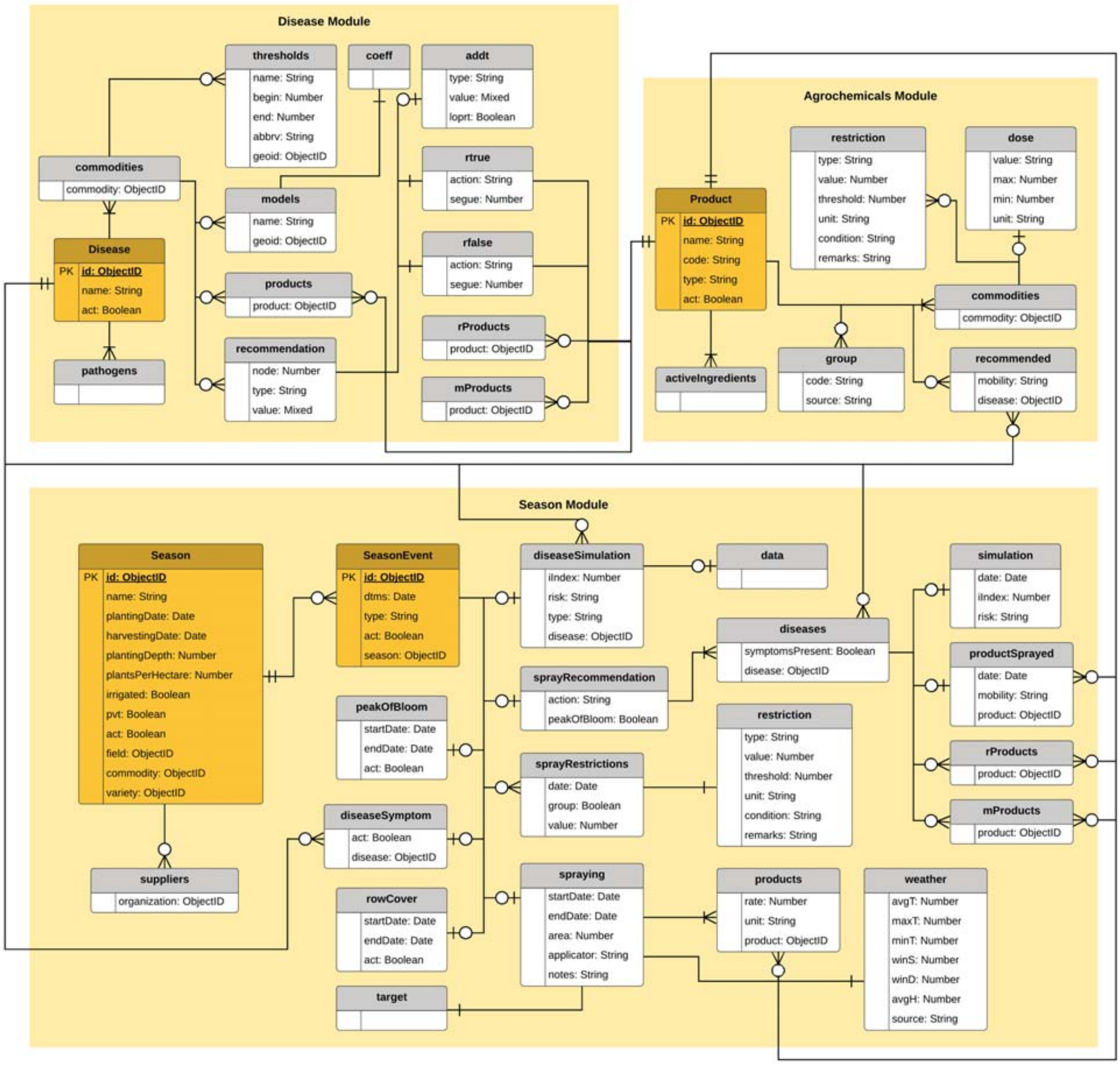


Figure 9. Logic entity relationship diagram (ERD) of Agrochemicals, Disease, and Season modules. Yellow entities represent the main documents of a module, while gray entities represent sub-documents.

3.2.1 Module Agrochemicals

This module was created and added to the existing AgroClimate structure specifically to control agrochemicals products, its recommendations, dosage, and specially spray restrictions. Figure 10 represents the Product.js class, as part of the Model representation layer. Where we can essentially note the following sub-documents:

```
var productSchema = new mongoose.Schema({
    name: {
        type: String,
        required: "Product name is required"
    },
    code: String,
    type: {
        type: String,
        required: "Product type name is required",
        enum: ['Fungicide', 'Insecticide', 'Herbicide']
    },
    activeIngredients: [],
    group: [{
        _id: false,
        code: String,
        source: String
    }],
    recommended: [{
        _id: false,
        disease: {
            type: mongoose.Schema.ObjectId,
            ref: 'Disease',
        },
        mobility: {
            type: String,
            required: "Product mobility is required",
            enum: ['Contact', 'Systemic', 'NA']
        }
    }],
    commodities: [{
        _id: false,
        id: {
            type: mongoose.Schema.ObjectId,
            ref: 'Commodity'
        },
        dose: {
            value: Number,
            max: Number,
            min: Number,
            unit: String
        },
        restrictions: [{
            _id: false,
            type: {
                type: String,
                enum: ['Rate', 'Spray', "Period"]
            },
            value: Number,
            threshold: String,
            unit: String,
            condition: String,
            remarks: String
        }]
    }],
    inf: {},
    __v: {
        type: Number,
        select: false
    }
    act: {
        type: Boolean,
        default: true,
        required: "Product status is required",
        select: false
    }
});
```

Figure 10. Product Model Class: Specifies product name, registration number, active ingredients, type, group, and recommended diseases use.

- ***Group* (Figure 10 lines 13 to 17)**: With the attributes *code* and *source* this sub-document is used to describe the fungicide groups codes from different sources (FRAC, MOA, etc..) and are populated in MongoDB BSON format, as follows:

  ```
  group: [{
      code: "M4",
      source: "FRAC"
  }]
  ```

  This specification becomes crucial when spray restrictions need to be enforced. By associating the group or mode of action of a fungicide to other recent sprays the system can trigger spray restrictions to the user.

- ***Recommended* (Figure 10 lines 18 to 29)**: To generate a spray recommendation, the system needs to address the infection index and its associated risk (Low, Moderate, or High) with recent spray applications, which depending of the product previously applied can repeal a pulverization effort. This process is controlled by SAS Pro Spray Recommendation Decision Tree (SRDT) and happens when two conditions are met:

  (a) A product recommended for the disease was applied within a specific period of time.

  (b) The product applied has a mobility type that suffices the treatment needed.

  The items above can have different thresholds with respect to the infection risk level at the moment of the request. More details on how SAS Pro SRDT works are explained in section 6.1.3.4.

- ***Restrictions* (Figure 10 lines 42 to 43)**: The commodity sub-document is used to describe commodity-specific parameters. A specific product can be used on different crops and consequently have different recommended dosages and use restrictions. Fungicide use restrictions can be grouped in three categories:

  (a) **Rate**: The maximum rate allowed by application or total of the season. The example below represents a rate restriction per application of the product *Switch 62.5 WG* (Attachment A).

  ```
  restrictions: [{
     type: "Rate",
     value: 14,
     threshold: "max",
     unit: "oz/acre",
     condition: "Application",
     remarks: ""
  }]
  ```

(b) **Spray**: Spray restrictions are used to limit the maximum number of consecutive sprays or total sprays in the season. The example below represents a spray restriction for maximum consecutive sprays of the product *Switch 62.5 WG* (Attachment A).

```
restrictions: [{
    type: "Spray",
    value: 2,
    threshold: "max",
    unit: "applications",
    condition: "Consecutive"
}]
```

(c) **Period**: A restriction for the minimum period for field re-entry, harvest, and/or planting. The example below represents a period restriction for minimum wait time for field re-entry of the product *Thiram* (Attachment A).

```
restrictions: [{
    type: "Period",
    value: 12,
    threshold: "min",
    unit: "hours,
    condition: "Reentry"
}]
```

More examples of spray restrictions are presented on Attachment A[16] [35].

3.2.2 Module Disease

The Disease module enables SAS Pro system to generate disease risks and recommendations by providing a generic commodity-based structure. Figure 11 represents the Disease.js model class. Where the following sub-documents can be highlighted:

- ***Thresholds*** **and** ***Models*** **(Figure 11 lines 12 to 32)**: These two sub-documents enable both the identification of pathogens different requirements of weather variables and its associated risk, as well as, the identification of the disease simulation model to be executed when new environmental conditions are reported by the automated weather stations (AWS).
- ***Products*** **(Figure 11 lines 33 to 36)**: The list of products that can be recommended by SAS Pro SRDT.

[16] Information provided in this table applies only to Florida, USA. Be sure to read a current product label before applying any chemical. The use of brand names and any mention or listing of commercial products or services in the publication does not imply endorsement by the University of Florida Cooperative Extension Service nor discrimination against similar products or services not mentioned.

```
var diseaseSchema = new mongoose.Schema({
    name: {
        type: String,
        required: "Disease name is required"
    },
    commodities: [{
        _id: false,
        id: {
            type: mongoose.Schema.ObjectId,
            ref: 'Commodity'
        },
        thresholds: [{
            name: String,
            begin: Number,
            end: Number,
            code: {
                type: String,
                enum: ['L', 'M', 'H']
            },
            geoid: {
                type: String,
                ref: 'Location'
            }
        }],
        models: [{
            name: String,
            geoid: {
                type: String,
                ref: 'Location'
            },
            coef: {}
        }],
        products: [{
            type: mongoose.Schema.ObjectId,
            ref: 'Product'
        }],
        recommendation: [{
            ...
        }]
    }],
    pathogens: [],
    inf: {},
    __v: {
        type: Number,
        select: false
    }
    act: {
        type: Boolean,
        default: true,
        required: "Disease status is required",
        select: false
    }
});
```

Figure 11. Disease Model Class: Includes disease name, pathogens, commodities affected, risk thresholds, and models for specific regions and weather conditions. The recommendation sub-document is being represented by three dots which indicate the expansion of its content in another figure.

- ***Recommendation* (Figure 12)**: This sub-document can be considered the core of the Disease module. It stores the logic behind the SAS Pro Spray Recommendation Decision Tree (SRDT). The structure it represents was implement with a generic approach where different decision tree requirements can be supported.

  The *Recommendation* sub-document (Figure 12) stores an array of nodes that together will form a binary tree. Inside each node there are instructions that are followed by a generic method on which the navigation to the tree extremities will occur. A common node example is represented below:

```
recommendation: [{
    _id: false,
    node: Number,
    type: {
        type: String,
        enum: ['Appl', 'Index', 'Date', 'Bloom', 'Symp', 'Mob', 'Stage']
    },
    value: mongoose.Schema.Types.Mixed,
    addt: [{
        type: {
            type: String,
            enum: ['Appl', 'Index', 'Date', 'Bloom', 'Symp', 'Mob', 'Stage']
        },
        value: mongoose.Schema.Types.Mixed,
        loprt: String
    }],
    rtrue: {
        action: {
            type: String,
            enum: ['N', 'S']
        },
        segue: Number,
        rProducts: [{
            type: mongoose.Schema.ObjectId,
            ref: 'Product'
        }],
        mProducts: [{
            type: mongoose.Schema.ObjectId,
            ref: 'Product'
        }]
    },
    rfalse: {
        action: {
            type: String,
            enum: ['N', 'S']
        },
        segue: Number,
        rProducts: [{
            type: mongoose.Schema.ObjectId,
            ref: 'Product'
        }],
        mProducts: [{
            type: mongoose.Schema.ObjectId,
            ref: 'Product'
        }]
    }
}]
```

Figure 12. Recommendation sub-document: Supports condition nodes for spray and products recommendation.

```
{
        node: 0,
        type: "Appl",
        value: 7,
        rfalse: {
            segue": 1,
        }
        rtrue: {
            action: "N",
        },
        addt: [{
            type: "Mob"
            loprt: "&&",
            value: "Systemic",
        }]
}
```

In the example above, the root node ***0*** (zero) has the following characteristics:

(a) Type ***Appl*** which represents a comparison of period since the last fungicide application.

(b) Comparison value of ***7*** (days).

(c) An additional comparison value *addt* of type ***Mob*** representing product mobility, with a logic operator (*loprt*) ***&&*** and a comparison value ***Systemic***.

(d) A binary result *rfalse* if one of the comparisons are not met. Which would imply a continuity (*segue*) to node ***1***.

(e) A binary result *rtrue* if both comparisons are met. Which would return the action ***N*** (No spray needed).

Considering these requirements, SAS Pro Spray Recommendation Tree (SRDT) would return the action ***N*** (No spray needed) specified on result ***rtrue***, if there was a recommended product applied in the past 7 days with a systemic mobility. Otherwise the method would continue to following node comparisons where a result could include spray and products recommendations as follows:

```
rfalse: {
    action: "S",
    rProducts: [
        ObjectId("5942ca31cd72b154719be18c"),
        ObjectId("59725334b387bf8b2848e986")
    ]
}
rtrue: {
    action: "S",
    rProducts: [
        ObjectId("5942ca31cd72b154719be18c"),
        ObjectId("59725334b387bf8b2848e986)"
    ],
    mProducts: [
        ObjectId("59726993b387bf8b2848e99e"),
        ObjectId("5972636fb387bf8b2848e99a")
    ],
}
```

In the case above, both results of the node imply a spray fungicide action (***S***), but with different products recommended in each case. In the ***rfalse*** result two fungicide products are recommended:

(a) ***Captan***:
Identifier 5942ca31cd72b154719be18c;
Registration number 34704-427;
Group M4.

(b) ***Thiram***:

Identifier 59725334b387bf8b2848e986;

Registration number 45728-26-400;

Group M3.

If all node conditions were met, the ***rtrue*** result would recommend the same fungicide products as above but to be mixed (***mProducts***) with other two:

(a) ***Elevate***:

Identifier 59726993b387bf8b2848e99e;

Registration number 66330-35;

Group 17.

(b) ***Fontelis***:

Identifier 5972636fb387bf8b2848e99a;

Registration number 352-834;

Group 7.

The different recommendations described above consider if the crop was currently in peak period of bloom. The complete decision tree for Anthracnose and Botrytis and other plant and season-specific decision factors, such as recent fungicide applications, disease infection index, and presence of symptoms, are presented in the Figures 13 and 14.

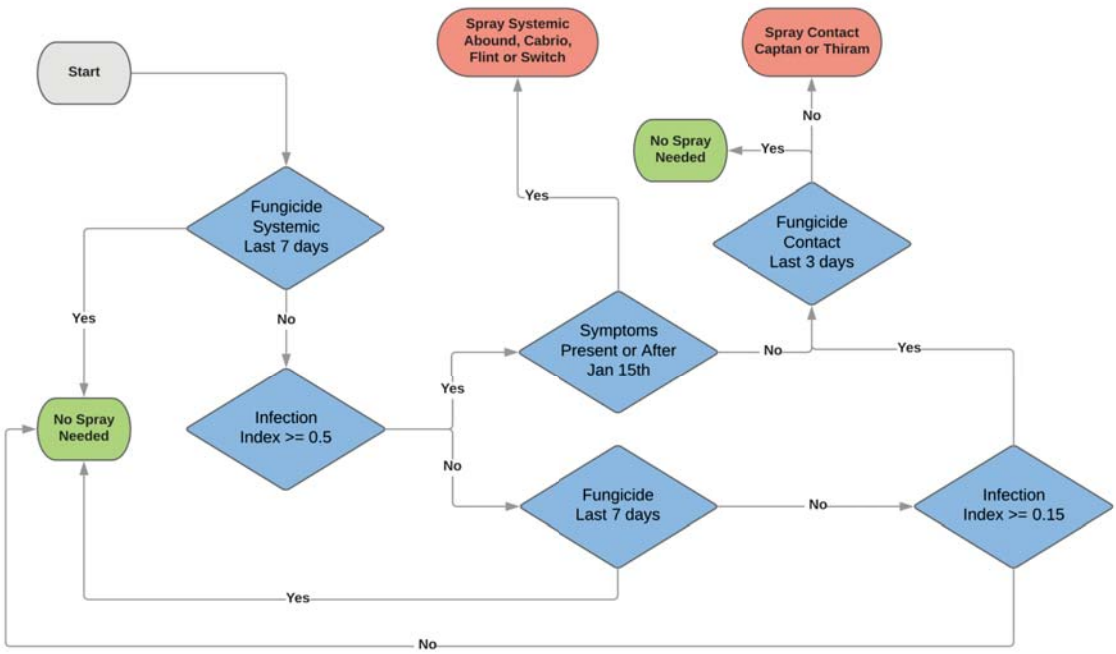


Figure 13. SAS Pro: Activity Diagram of Anthracnose Spray Recommendation Decision Tree. Latest fungicide application, disease infection index, and presence of symptoms information is used to generate a spray recommendation.

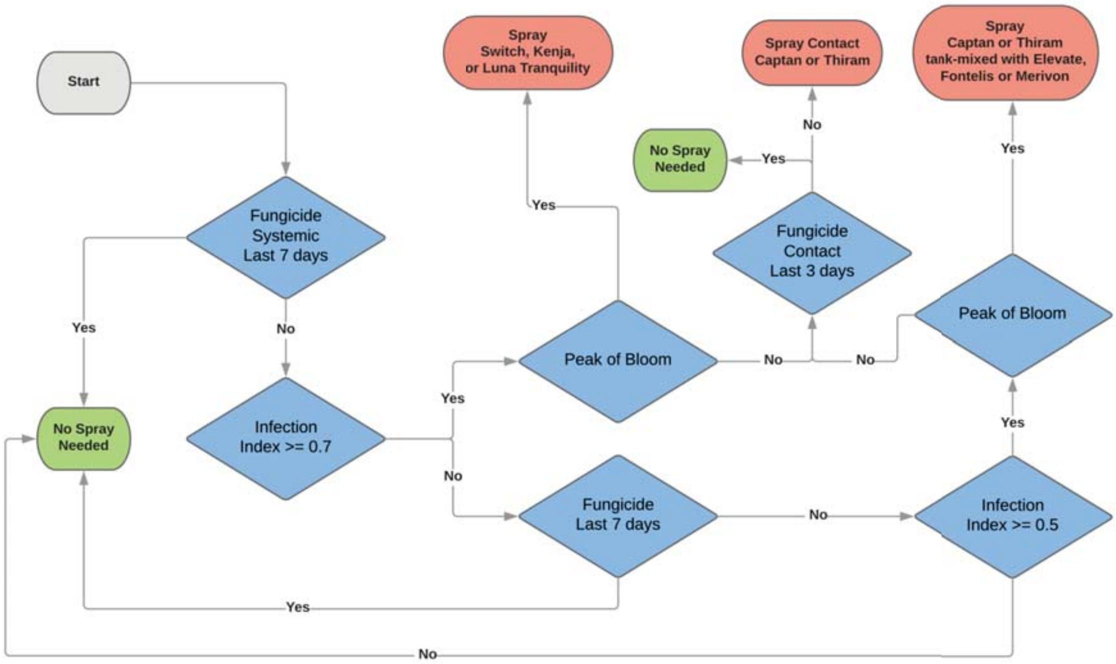


Figure 14. SAS Pro: Activity Diagram of Botrytis Spray Recommendation Decision Tree. Latest fungicide application, disease infection index, and phenological stage information is used to generate a spray recommendation.

3.2.3 Module Season

Besides containing the structure needed for a season registration and management, the Season module also comprises sub-documents for required events that serve as input to the SAS Pro Spray Recommendation Decision Tree (SRDT). These weather, plant, and operational related events are specified in the seasonEvent.js class (Figure 15). Where the following season event sub-documents require detailed explanation:

- ***Disease Simulation* (Figure 16)**: Disease simulation events are the output of disease infection models, which gather weather parameters to estimate infection indexes every 15 minutes. These sub-documents are tailored for each supported disease and present the following attributes:

  (a) **Infection Index (*iIndex*)**: The infection index simulated by the disease model.

  (b) **Risk**: The associated risk of a given infection index according to a disease-defined threshold for Low Risk (**L**), Moderate Risk (**M**), and High Risk (**H**).

  (c) **Type**: The type of simulation, Forecast (**F**) or Observed (**O**).

  (d) **Data**: Additional weather parameters used in the generation of the disease simulation such as Leaf Wetness Duration (**LWD**) and Temperature (**avgT**).

```
var seasonEventSchema = new mongoose.Schema({
    dtme: String,
    dtms: 'Moment',
    season: {
        type: mongoose.Schema.ObjectId,
        ref: 'Season',
        required: "Season is required"
    },
    type: {
        type: String,
        enum: ["info", "warning", "alert", "weather", "note", "recommendation",
        "diseaseSimulation", "sprayRecommendation", "sprayRestrictions",
        "spraying", "peakOfBloom", "diseaseSymptom", "rowCover"]
    },
    diseaseSimulation: {
        ...
    },
    sprayRecommendation: {
        ...
    },
    peakOfBloom: {
        act: Boolean,
        startDate: 'Moment',
        endDate: 'Moment'
    },
    diseaseSymptom: {
        disease: {
            type: mongoose.Schema.ObjectId,
            ref: 'Disease',
        },
        act: Boolean
    },
    spraying: {
        ...
    },
    sprayRestrictions: [{
        ...
    }],
    rowCover: {
        act: Boolean,
        startDate: 'Moment',
        endDate: 'Moment'
    },
    inf: {},
    act: {
        type: Boolean,
        default: true,
        required: "Season event status is required"
    }
});
```

Figure 15. Season Event Model Class: Supports different event types occurring during the crop season. Including disease simulations, spray recommendations, spray restrictions, and pulverization. The sub-documents represented by three dots have their content expanded in another figures.

```
diseaseSimulation: {
    disease: {
        type: mongoose.Schema.ObjectId,
        ref: 'Disease',
    },
    iIndex: Number,
    risk: {
        type: String,
        enum: ['L', 'M', 'H']
    },
    type: {
        type: String,
        enum: ['F', 'O']
    },
    data: {}, //LWD, temperature...
    inf: {
        dtgr: String
    }
}
```

Figure 16. Disease Simulation sub-document: Includes information about observed and forecasted disease risk and environmental conditions.

- ***Spray Recommendation* (Figure 17)**: Spray Recommendation events are generated by SAS Pro SRDT and take in consideration other events of the season. Four different actions can be presented to the users (Figure 17, line 4):

  (a) **Low Infection Index (L)**: Represents a No Spray Needed action due to low infection indexes observed in the past days.

(b) **No Spray Needed (N)**: A action to not spray even though infection risks were observed. This action is generally associated with a recent fungicide application that is on the period range required for plant protection against a give pathogen. See ***productSprayed*** sub-document (Figure 17 lines 21 to 25).

(c) **Answer Questionnaire (Q)**: A spray action that needs complementary information from the user to generate an actual spray and product recommendation.

(d) **Spray Fungicide (S)**: A spray recommendation which will always present recommended products (***rProducts***), with a contingent sub-document (***mProducts***) containing a list of products to be tank-mixed.

```
1   sprayRecommendation: {
2       action: {
3           type: String,
4           enum: ['L', 'N', 'Q', 'S']
5       },
6       peakBloom: Boolean,
7       diseases: [{
8           _id: false,
9           disease: {
10              type: mongoose.Schema.ObjectId,
11              ref: 'Disease',
12          },
13          simulation: {
14              date: 'Moment',
15              iIndex: Number,
16              risk: {
17                  type: String,
18                  enum: ['L', 'M', 'H']
19              }
20          },
21          productSprayed: {
22              date: 'Moment',
23              product: String,
24              mobility: String,
25          },
26          symptomsPresent: Boolean,
27          rProducts: [{
28              type: mongoose.Schema.ObjectId,
29              ref: 'Product',
30          }],
31          mProducts: [{
32              type: mongoose.Schema.ObjectId,
33              ref: 'Product',
34          }]
35      }]
36  }
```

Figure 17. Spray Recommendation sub-document: Includes spray action, product recommendation for each supported disease, reference simulation or product application.

Information of current bloom period, symptoms present, simulation, and sprayed products are used in the recommendations and kept on the Spray Recommendation sub-document for reference. The snippet below represents a typical spray recommendation event:

```
sprayRecommendation: {
    action: "S",
    peakBloom: true,
    diseases: [
        {
```

```
6.              disease: ObjectId("59a81dee707cbe4640bfa8fd"),
7.              symptomsPresent: false,
8.              mProducts: [
9.              ],
10.             rProducts: [
11.                 ObjectId("5942ca31cd72b154719be18c"),
12.                 ObjectId("59725334b387bf8b2848e986")
13.             ],
14.             simulation: {
15.                 iIndex: 0.385,
16.                 risk: "M",
17.                 date: 1518545700000.0
18.             }
19.         },
20.         {
21.             disease: ObjectId("59a81be7707cbe4640bfa8fb"),
22.             symptomsPresent: false,
23.             mProducts: [
24.                 ObjectId("59726993b387bf8b2848e99e"),
25.                 ObjectId("5972636fb387bf8b2848e99a"),
26.                 ObjectId("59721d44c4f53e0e66de527f")
27.             ],
28.             rProducts: [
29.                 ObjectId("5942ca31cd72b154719be18c"),
30.                 ObjectId("59725334b387bf8b2848e986")
31.             ],
32.             simulation: {
33.                 iIndex: 0.5206,
34.                 risk: "M",
35.                 date: 1518115500000.0
36.             }
37.         }
38.     ]
38. }
```

Where:

- ***Peak of Bloom* (Figure 15, lines 21 to 25)**: This user-enabled event is used to address if the crop is currently in its peak of bloom period. Growers can inform the estimated end of the period so the system does not need to repeatedly request this information.

- ***Disease Symptom* (Figure 15 lines 26 to 32)**: Similarly to peak of bloom, users can inform if the plant presents symptoms of a given disease. Both peak of bloom and disease symptom information can drive different product recommendations following SAS Pro SRDT node conditions.

- ***Spraying* (Figure 15 line 33, expanded on 18)**: A sub-document that stores recent spray events input by the user. Spraying events have fundamental decision influence to address if a field is protected against an observed infection risk, considering spraying date and product fitting to combat the pathogen.

```
spraying: {
    _id: false,
    startDate: 'Moment',
    endDate: 'Moment',
    products: [{
        rate: Number,
        unit: String,
        product: {
            type: mongoose.Schema.ObjectId,
            ref: 'Product'
        }
    }],
    notes: String,
    applicator: String,
    area: Number,
    weather: {
        avgT: Number,
        maxT: Number,
        minT: Number,
        winS: Number,
        winD: Number,
        avgH: Number,
        source: String
    },
    target: {}
}
```

Figure 18. Spraying sub-document: Includes information about a performed spray event such as product sprayed, rate, and weather conditions at the time of spraying.

- ***Spray Restrictions* (Figure 19)**: Spray restrictions are a consequence of spraying input by the user. Each fungicide product has associated restrictions in its database document. When a product is used, its restrictions can become active to the target field, theses restrictions can be temporary in the following cases:

```
sprayRestrictions: [{
    date: 'Moment',
    group: String,
    value: Number,
    restriction: {
        type: {
            type: String,
            enum: ['Rate', 'Spray', "Period"]
        },
        value: Number,
        threshold: String,
        unit: String,
        condition: String,
        remarks: String
    }
}]
```

Figure 19. Spray Restrictions sub-document: Includes information about a restriction generated due to recent spray events. Including date, group affected, value reached, and reference restriction.

(a) **Spray Restrictions**: This type of restriction comprises limitations on a product use. Spray restrictions limiting consecutive applications can be voided when a following spray event is registered and includes products of different, not currently restricted groups. However, a same type spray restriction with a limit per season will persists till harvest.

(b) **Period Restrictions**: Period restrictions, by its nature, have a period of time, generally hours or days, in which they will remain active. After the stated period is passed, the restriction is no longer presented to the user.

Examples include:

```
sprayRestrictions: [
    {
        group: "11",
        date: 1518453310000.0,
        value: 3,
        restriction: {
            type: "Spray",
            value: 2,
            threshold: "max",
            unit: "applications",
            condition: "Consecutive"
        }
    },
    {
        group: "11",
        date: 1518453310000.0,
        restriction: {
            type: "Period",
            value: 4,
            threshold: "min",
            unit: "hrs",
            condition: "Reentry"
        }
    }]
```

3.3 MOBILE APPLICATION

The main goal of SAS Pro mobile application is to provide an automated tool to help strawberry producers in Florida, USA, monitor and forecast disease infection risk, decide about spraying, and manage fungicide resistance.

SAS Pro was developed for iOS and Android operating system, using the official tools and programming languages provided by Apple® (Swift and iOS SDK) and Google® (Java and Android SDK) respectively. It manages requests and input information for data persistence in the AgroClimate Database by using specific cloud services of AgroClimate Services API. Information entered by the user through the mobile application - such as spray reports - are used to assess future spray recommendations as part of the disease risk and fungicide resistance management models.

Throughout the development process, prototype versions were made available to stakeholders for testing and validation of features. The application follows a MVC (Model View Controller) design pattern, where:

- **Model**: Responsible for managing database objects, disease model results and associated methods.
- **View**: Data presentation and user interaction, supporting visualization of disease risks, simulation graphs and user inputs.
- **Controller**: Interface between Model and View. Controls all the system logic, including events handling and calls to AgroClimate Services API.

Different native and third-party libraries and frameworks were used to provide all needed functionalities of the mobile apps. Some of them are described in the following sections.

3.3.1 Map and Location Services

Considering the geographic nature of the proposed platform, where disease risks are generated for specific regions and environmental readings, mapping and location functionalities are used as enablers for geolocated data input and visualization.

Apple and Google Maps were used to present geographic information in the iOS and Android apps respectively. The Map Kit and Google Maps Framework provide all methods and protocols required for satellite imagery, map annotations, overlays, and reverse-geocoding.

3.3.2 Dataset Visualization

Great volume of data generally requires chart interfaces for users to better address a specific variable magnitude and its deviation during a period of time. On SAS Pro this is the case for disease infection indexes, where producers are able to visualize and interact with current and forecast disease risks on a graph interface.

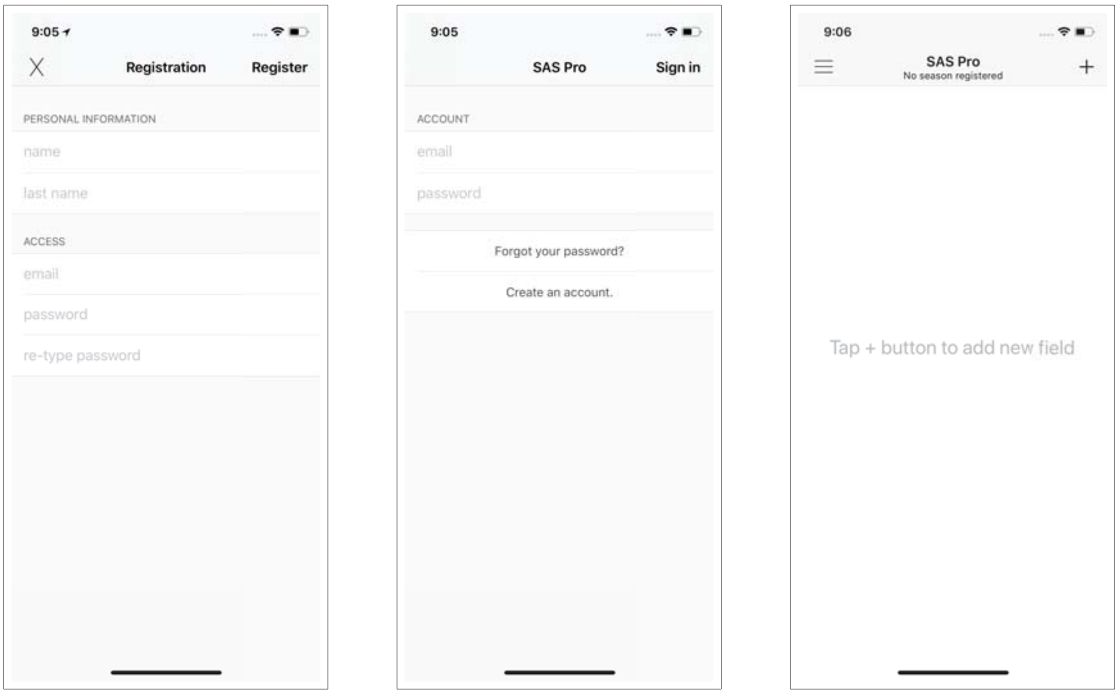
The third-party Scrollable Graph View [53] framework was used to display graph content on the iOS version of SAS Pro. While on Android, the framework Hello Chars [54] was used. It has compatibility with API 8+ (Android 2.2), although its use is recommended from API 14 (Android 4.0) and up, due to Hardware Acceleration capabilities available on these versions. These frameworks provide a complete set of Line, Bar, and Dot charts with great customization options and easy integration on existing iOS and Android projects.

3.3.3 Managing Fields and Seasons

Fields and seasons serve as base to all features of SAS Pro. Fields are responsible for location and reference weather data sources while season info group disease simulations, recommendations, and spraying events.

3.3.3.1 Adding Fields

After user registration (Figure 20(a)) or login (Figure 20(b)), fields can be added by tapping the Add Field button in the top right corner of the main screen (Figure 20(c)).



(a) SAS Pro: User Registration. Name, email and password are required.

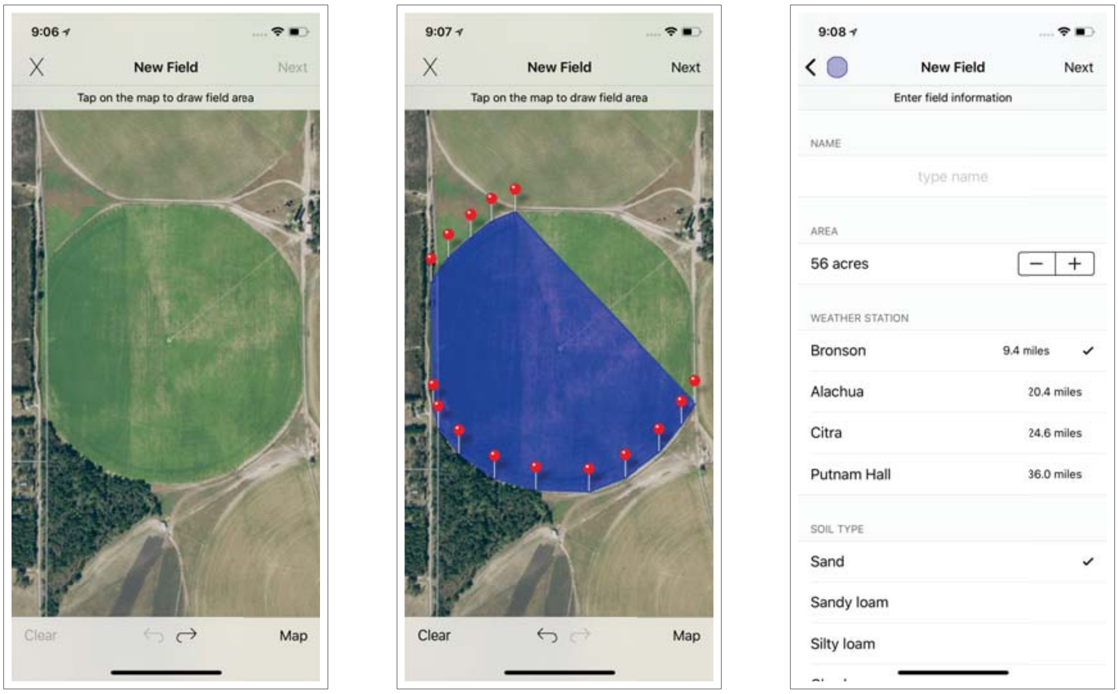
(b) SAS Pro: User Login. Email and password are used to sign in.

(c) SAS Pro: Add new field option presented in the main screen after user login.

Figure 20. SAS Pro: User Registration and Login interfaces. After login, the main screen of the app is presented with the option to register a field.

When the Add New Field option is selected, users are presented with a map-based interface that automatically zooms in to the user current location (Figure 21(a)). This interface guides the user to draw the shape of the field by tapping on the map. While tapping, location pins are added and a polygon starts to form. Users can adjust the coordinates of each pin by dragging them on the map. There are also options located on the bottom of the screen capable of undoing recent changes or even completely clean the map to restart the process (Figure 21(b)).

The next step on a field registration is to enter a name, adjust the area (pre-calculated by the drawn polygon of the previous step), select the reference weather station, and soil type (Figure 21(c)). The selected weather station is used as reference of environmental readings to generate disease simulations for active seasons of this field.



(a) SAS Pro: Selecting field location and area.

(b) SAS Pro: Drawing the area of the field.

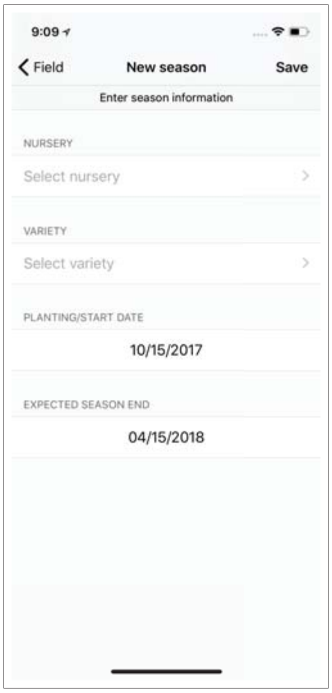
(c) SAS Pro: Entering new field information.

Figure 21. SAS Pro: Adding a new field. Users need to select field location, draw field area, and enter field information such as name, area, reference weather station, and soil type.

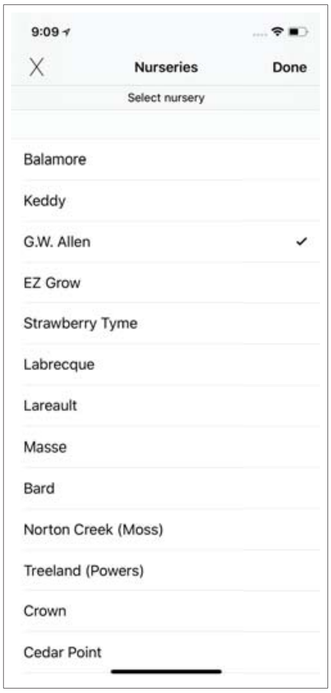
3.3.3.2 Adding Seasons

After a field is set, the last step is to select the information of the season (Figure 22(a)). Users need to select the nursery from which the transplanted plants originate[17] (Figure 22(b)), plant variety (Figure 22(c)), as well as, planting and expected season end dates. Once the season is saved, the main screen of SAS Pro will display the registered field under a section called No Disease Simulation (Figure 23(a) and 23(b)). When the Disease Simulation models and SAS Pro SRDT are executed, the field will then display a recommended action as presented on Figure 23(c).

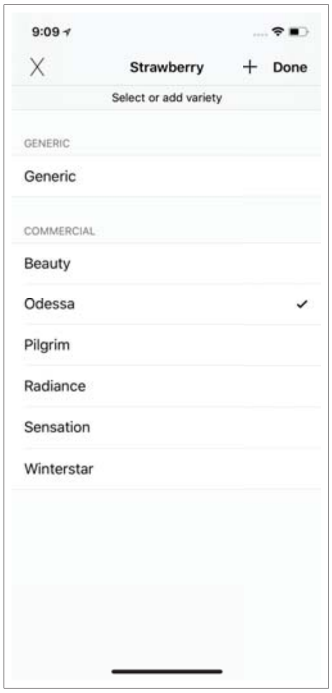
[17] Nursery info is used to send custom alerts to users in case abnormal fungicide resistance is observed and associated with transplanted plants from a specific nursery.



(a) SAS Pro: Adding a season. Nursery, variety, and season dates are required.

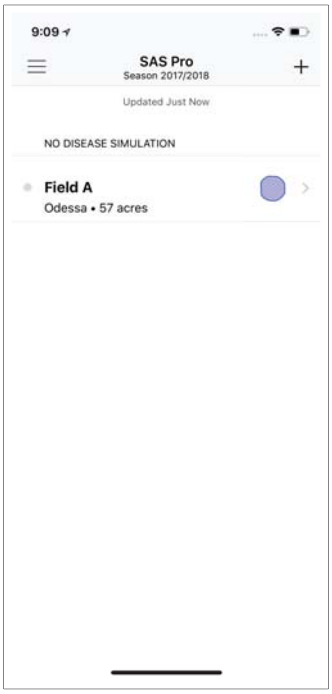


(b) SAS Pro: Selecting the nursery from which the transplanted plants originate.

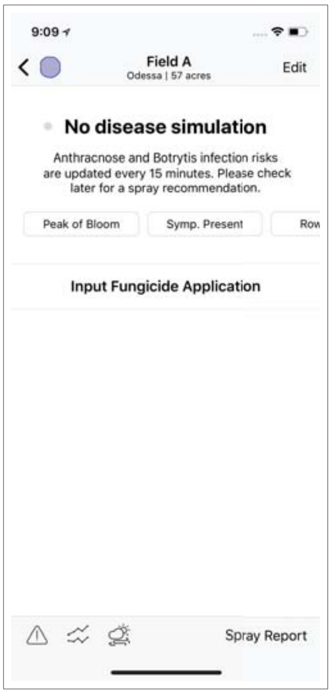


(c) SAS Pro: Selecting plant variety. Users can select commercial or generic varieties.

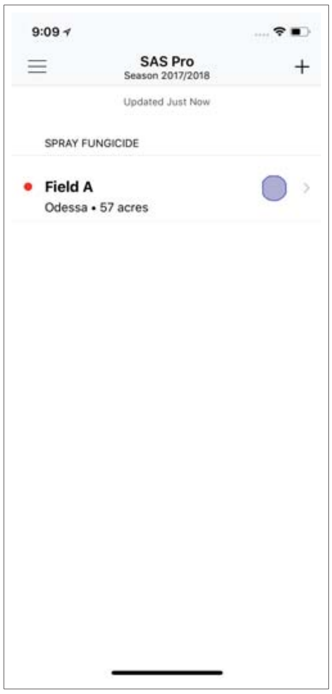
Figure 22. SAS Pro: Entering new season information. Users need to select the nursery from which the transplanted plants originate, plant variety, planting date and expected season end.



(a) SAS Pro: No Disease Simulation section, a temporary condition for recently added fields.



(b) SAS Pro: Detailed recommendation when no disease simulation is available.



(c) SAS Pro: Spray action after disease simulation and SRDT models are executed.

Figure 23. SAS Pro: Recently added fields are grouped under the No Disease Simulation section. After disease simulation and SRDT models are executed, a spray recommendation is generated.

3.3.4 Disease Simulation and Recommendations

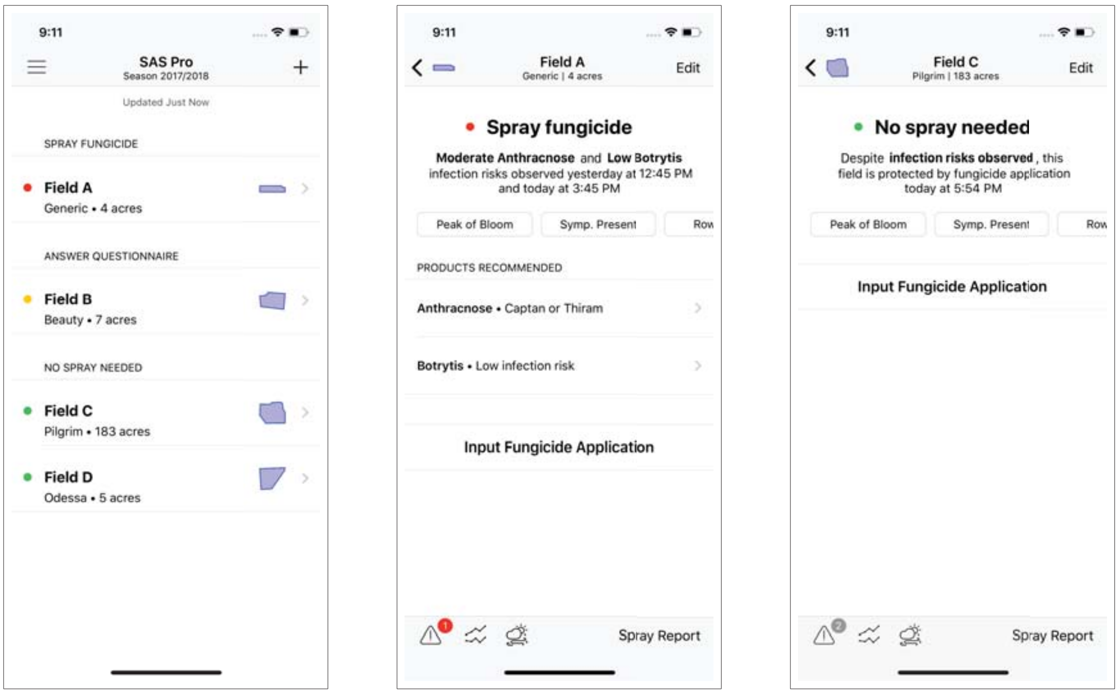
SAS Pro was designed to easily inform critical recommended actions to the users right on the first screen. The list of fields of a current season is grouped by four possible actions (Figure 24(a)) in the following order:

(a) **Spray Fungicide**: Represented by the color red, this is a high priority action. Always the topmost group when not empty.

(b) **Answer Questionnaire**: A spray action that needs complementary information from the user to generate an actual spray and product recommendation. Represented by the orange color.

(c) **No Spray Needed**: A group of fields with action to not spray. It can represents that no considerable infections indexes were observed for the fields in this group, or that the fields are protected by recent fungicide application.

(d) **No Disease Simulation**: Meaning that no action was defined yet. This is a temporary group on the main screen represented by light gray color. Generally associated with recently added fields.



(a) SAS Pro: Season 2017/2018 list of fields grouped by action.

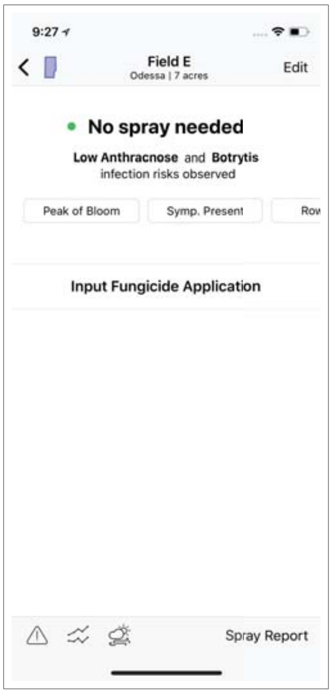
(b) SAS Pro: Spray and products recommendation screen.

(c) SAS Pro: No Spray Needed, due to recent protective spray.

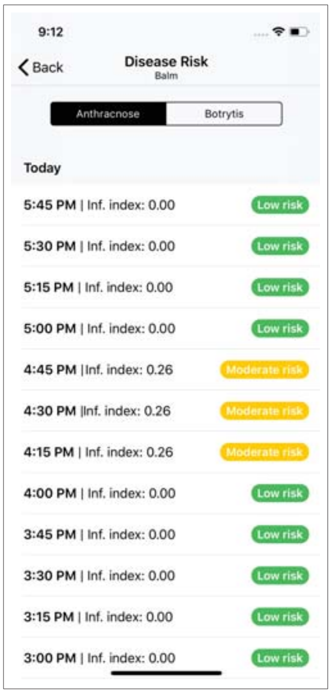
Figure 24. SAS Pro: Registered fields grouped by action. Priority actions are presented in red and listed on the top. When selecting a field, detailed spray and products recommendation is presented.

When selecting a field, a new screen with detailed spray and product recommendation is presented. On the top part of the screen users have access to the spray action followed by a brief explanation of the recommendation. On the mid part of the screen, if the action is to spray fungicide, the products recommended for each supported disease are presented (Figure 24(b)). Figure 24(b), 24(c) and 25(a) details three types of spray recommendations that can be presented to the user, along with product recommendations.

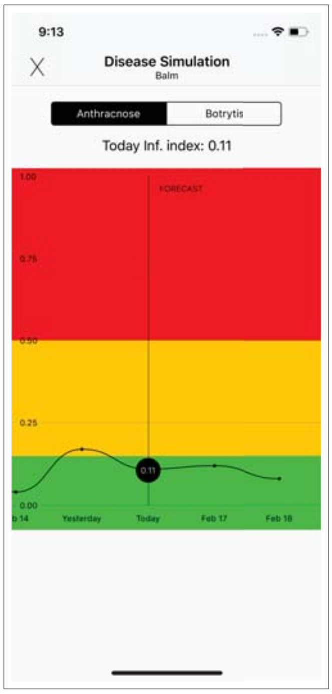
Disease simulations can be accessed by selecting the highlighted risk information of each disease on the risk description below the recommended action. On Figure 25(b), a list with past seven days simulated infection risks is presented and grouped by day. Time, infection index, and risk indication is provided. Users can also access a disease simulation graph with the maximum daily observed risk of the past thirty days, and next two days disease risk forecast (Figure 25(c)).



(a) SAS Pro: No Spray Needed recommendation due to low infection risks observed.



(b) SAS Pro: Disease infection risk simulated in the past seven days.



(c) SAS Pro: Disease Simulation Graph for observed and forecasted disease risk.

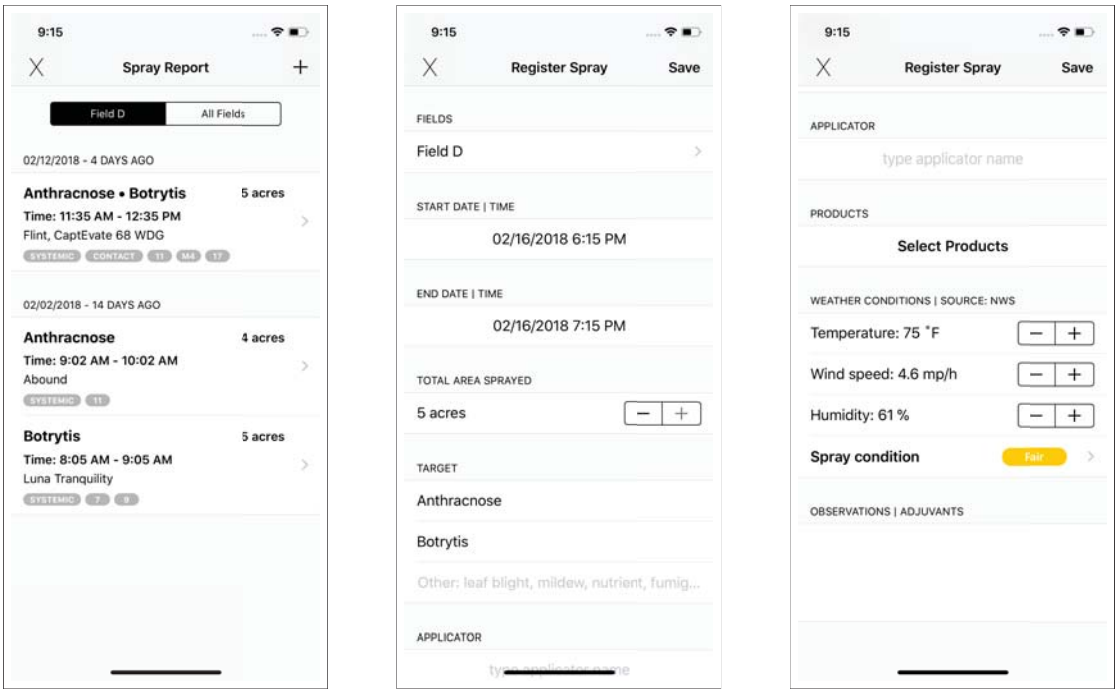
Figure 25. SAS Pro: Recommendation to not spray due to low infection indexes observed. Access to disease simulations and risks in the past thirty days.

3.3.5 Spray Report, Restrictions, and Weather conditions

Spray Report functionality in SAS Pro gives growers a simple template to register fungicides applications performed in the field. This information is used by SRDT to address if a particular field is protected against an observed pathogen infection risk. Weather conditions can be reviewed when planning a spraying operation on the field. This is an important step when aiming for maximum efficacy on disease control and spraying safety. As spraying events are registered in the app, spray restrictions can be generated for specific fungicide groups.

3.3.5.1 Entering Fungicide Applications

The Spray Report option accessed from the recommendation screen lists all recent fungicide applications of the selected field or all fields of the season (Figure 26(a)). Users can input new spray events on the selected field or add additional fields where the same products were applied. Start and end date of the spray need to be selected along with the total area sprayed, spray target, applicator name, products applied, and adjuvants (Figure 26(b) and 26(c)). Current and forecasted weather data are automatically pulled from the National Weather Service so users can address if meteorological conditions are optimal for spraying operations. More details on defining spraying conditions are presented in the following section.



(a) SAS Pro: Recent fungicide applications performed on selected field.

(b) SAS Pro: New spray. Selecting period, area, and target.

(c) SAS Pro: New Spray. Inputing applicator, products, and adjuvants.

Figure 26. SAS Pro: Recent fungicide applications and registration of new sprays. Users select period, area sprayed, target, applicator name, products applied, and weather conditions.

3.3.5.2 Weather Conditions

When preparing for a spraying operation, growers reportedly check local weather sources to decide the best time for pulverization. Besides health and environmental risks, adverse meteorological conditions can cause inefficient controls of diseases and should be avoided when spraying a field.

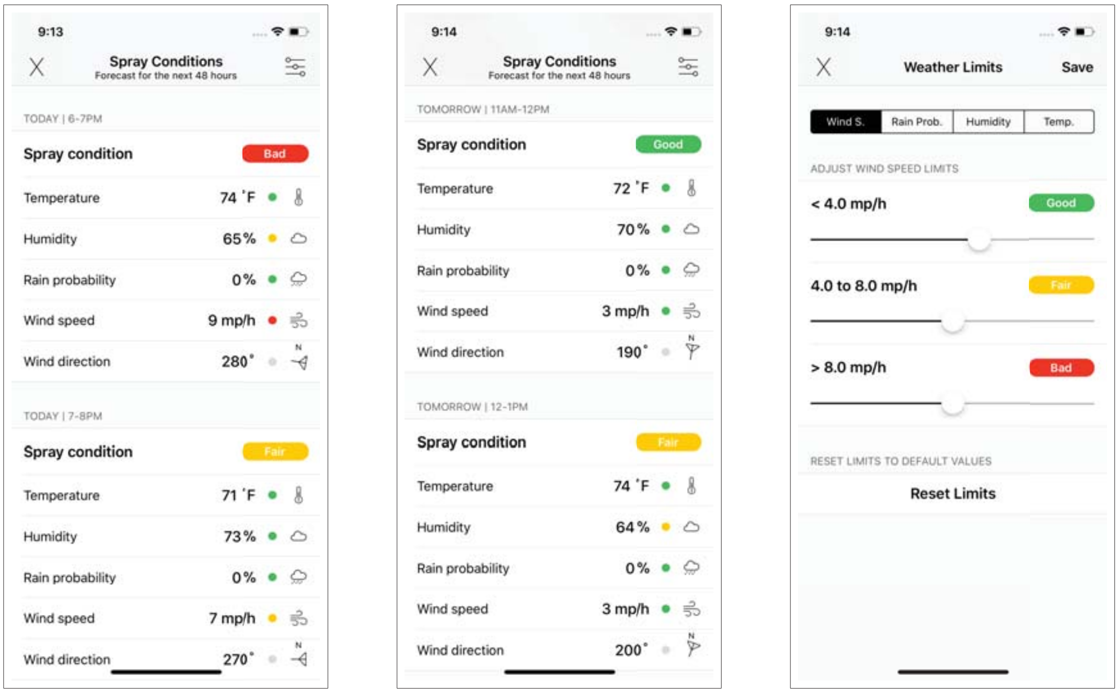
SAS Pro makes easier for strawberry growers to decide the best spraying time and adjust meteorological thresholds according to their needs. On the Recommendation screen users can access the Spray Conditions interface where next 48 hours National Weather Service (NWS) forecast data is used to address current and future weather conditions.

On Figure 27(a), bad and fair spraying conditions are being reported for the following hours. Users can scroll to next hours and days to find a period with good weather conditions for spraying (Figure 27(b)). Four weather variables are used for this estimation and can be addressed individually according its color indication:

(a) **Temperature and Relative Humidity**: High temperatures and low humidity are associated with spray droplets evaporation, causing loss of active ingredients that will not deposit in the plant surface.

(b) **Rain Probability**: Precipitation during a pulverization will cause the product applied to be washed out from the plant, causing inefficiency in the disease control. Rain probability is a factor that needs to be considered during spraying events and the following hours.

(c) **Wind Speed**: Considered a critical factor for spray drift [43]. High wind speed velocities may carry spray droplets away from its target. Depending on toxicity of the active ingredients being applied, spray drift, can be hazardous to humans and other species of animals and plants [36].



(a) SAS Pro: Bad and Fair spraying conditions due to high wind speed values.

(b) Better spraying conditions according to next hours weather forecast.

(c) SAS Pro: Adjusting thresholds for wind speed, rain probability, relative humidity, and temperature.

Figure 27. SAS Pro: Forecast of spraying conditions for the next 48 hours. Thresholds for good, fair, and bad conditions can be adjusted for each supported weather variable.

Default thresholds for each weather variable - wind speed[18], rain probability[19], humidity[20], and temperature[21] - are used to address Good, Fair, or Bad spraying conditions [55]. Users can tap the top right button on the Spray Conditions screen (Figure 27(b)) to adjust these thresholds to better meet their needs (Figure 27(c)). The recommendations will reflect the changes performed and there is always the option to reset the thresholds to its default values, if desired.

3.3.5.3 Spray Restrictions

Fungicide resistance guidelines comprise important directions on fungicide rotation with the goal of minimizing the build of resistance in a variety of pathogens. SAS Pro was designed to integrate these guidelines and inform users about restrictions that may apply according to in-season spraying events. SAS Pro keeps track of recently applied products and its interaction with other fungicide applications. It adjusts product recommendations enabling a better product rotation and consequently less risk of resistance development.

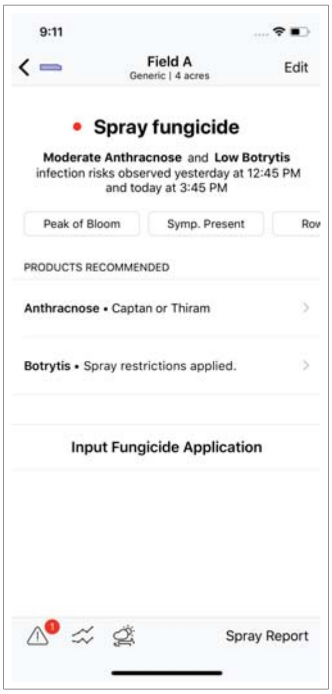
Spray restrictions in SAS Pro are highlighted according to its priority in the bottom bar of the spray recommendation screen, showing the number of currently active restrictions and a color to differentiate critical restrictions to advisory information. Product recommendations can also be affected by spray restrictions, where fungicides that have its group restricted will not be recommended. As exhibited in the mid section of Figure 28(a), with the message *"Spray restrictions applied"*.

On the restrictions screen, details of active restrictions are presented and grouped by date (Figure 28(b)). The red color is used to represent restrictions that limit a product use, described as spray restrictions. While the gray color is associated with restrictions of advisory character such as period restrictions for field re-entry, harvest, or planting buffers.

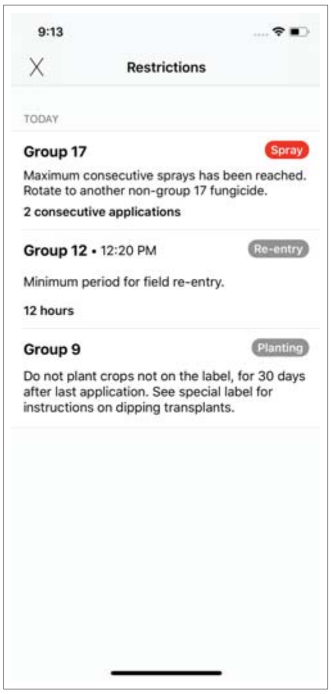
Considering the importance of following resistance management guidelines, the fungicide list presented when registering a spray event will display labels for products of groups with active restrictions, alerting users that the use of these products are not recommended (Figure 28(c)).

---

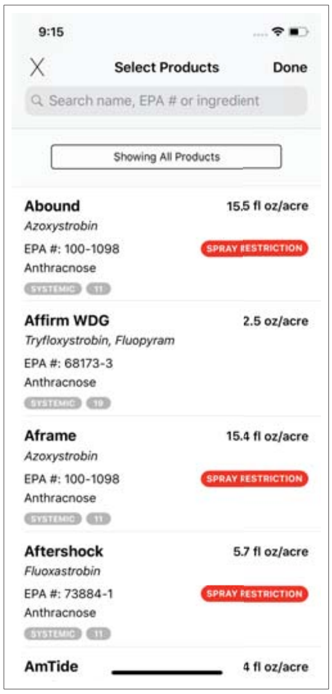
[18] Wind speed: Good <4.0mp/h | Fair 4.0-8.0mp/h | Bad >8.0mp/h
[19] Rain probability: Good <25% | Fair 25-50% | Bad >50%
[20] Humidity: Good >70% | Fair 50-70% | Bad <50%
[21] Temperature: Good < 80°F | Fair 80-92°F | Bad >92°F



(a) SAS Pro: Restrictions menu option on the recommendation screen.



(b) SAS Pro: List of active spray and period restrictions for a selected field.



(c) SAS Pro: Indicative label on products with active spray restrictions.

Figure 28. SAS Pro: Active Spray Restrictions for fungicide groups. When selecting products for a spray registration, fungicides from restricted groups present a label to indicate that its use is not recommended.

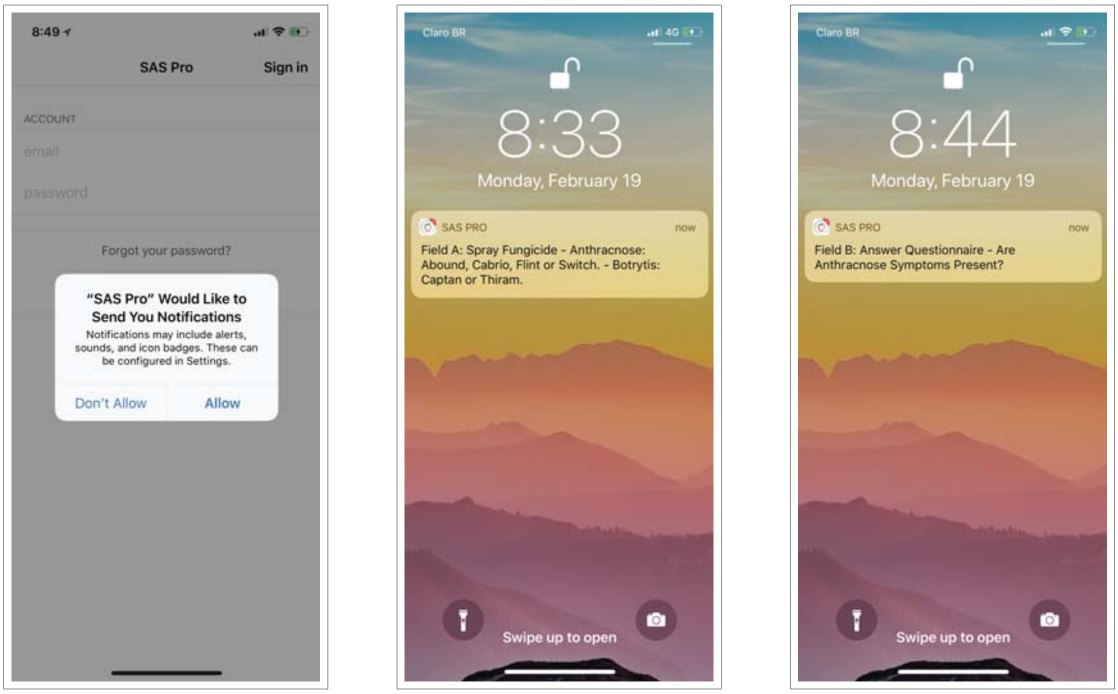
3.3.6 Push Notifications

Critical information is sent to users via remote notifications using Apple Push Notification Service (APNS) and Google Cloud Messaging (GCM) protocols. Push notifications are an effective way to reach users. They work similarly as text messages but are sent over internet connection and provide a bigger array of options for user interaction.

Permission from the user is required to enable the receiving of push notifications on both iOS and Android platforms (Figure 29(a)). With permission granted, a unique device/app token is generated and can be used to send messages and data to a specific device and user. Calls to APNS and GCM services required a similar JSON formatted structure, an example of APNS body call is presented below:

```
{
  "aps":{
    "alert": "My Push Notification!",
    "sound": "default"
  }
  "data": "My custon JSON data"
}
```

Due to the automated nature of SAS Pro, notifications include spray and products recommendations (Figure 29(b)). Which promptly inform users that then can open the app to check more details or register a spray application. SAS Pro also notifies users when additional information is required to define a spray recommendation as presented in Figure 29(c).



(a) SAS Pro: Permission request to receive remote notifications.

(b) SAS Pro Notifications: Spray and product recommendation for a specific field.

(c) SAS Pro Notifications: Requesting additional information to the user.

Figure 29. SAS Pro Notifications: Users permission to receive remote notifications which can include alerts of disease risk and products recommendations.

4. TESTS AND RESULTS

During the 2017/2018 strawberry season in Florida, USA, the developed system was tested and some features were observed. This section presents a discussion on both structure and use tests.

4.1 GENERIC STRUCTURE FOR DISEASE APPLICATIONS

The developed structure - expanded from existing AgroClimate Services (AS) - provides a generic foundation for disease alert systems. Different spray recommendation needs can be easily integrated in the SRDT with the addition of custom nodes.

Two commodities, strawberry and citrus, and three fungi-based diseases are currently supported by SRDT and being used with the following characteristics:

(a) **Anthracnose**: Primarily considers recent fungicide applications and infection thresholds. If infection risk is high, season period and presence of symptoms will designate an appropriate product recommendation.

(b) **Botrytis**: Similarly to the Anthracnose decision tree nodes, Botrytis conditions are also based on recent fungicide applications and infection thresholds with the addition of phenology information for current peak of bloom which needs to be requested to the user since is not a easily predictable stage and may occur multiple times on the season.

(c) **Postbloom Fruit Drop (PFD)**: An important disease on citrus production, PFD is caused be the same pathogen as Anthracnose on strawberries and other small fruits, *Colletotrichum acutatum* [56]. For PFD spray recommendations, information on phenological stages and recent fungicide applications are used to decide if spray is needed or not. Then, infection indexes are used to recommend different products.

Spray recommendations can be accessed using a specific route of the Disease module: **http://:domain/:service/:version/recommend/commodity/:id**. The following set of parameters serve as input to the Anthracnose and Botrytis SRDT:

```
{
   params: {
      diseases: [
         {
            diseaseId: "59a81dee707cbe4640bfa8fd",
            daysLastAppl: 10,
            productMobility: "Contact",
            symptomsPresent: true,
```

```
        iIndex: 0.7
      },
      {
        diseaseId: "59a81be7707cbe4640bfa8fb",
        daysLastAppl: 9,
        productMobility: "Contact",
        symptomsPresent: false,
        iIndex: 0.9
      }
    ],
    peakOfBloom: true
  }
}
```

The call above will return an action, Spray Fungicide (***S***) or No Spray Needed (***N***). In case of an action to spray, the result will also contain a list of products recommended (***rProducts***), and a contingent list of products to be tank-mixed (***mProducts***), for each supported disease as presented below:

```
{
  data: {
    action: "S",
    diseases: [
      {
        _id: "59a81dee707cbe4640bfa8fd",
        name: "Anthracnose",
        rProducts: [
          "5942d8e5be15f654ffe6fba8",
          "5972198dc4f53e0e66de527b",
          "59721a6cc4f53e0e66de527c",
          "5942d6cbbe15f654ffe6fba7"
        ],
        mProducts: []
      },
      {
        _id: "59a81be7707cbe4640bfa8fb",
        name: "Botrytis",
        rProducts: [
          "5942ca31cd72b154719be18c",
          "59725334b387bf8b2848e986"
        ],
```

```
            mProducts: []
        }
    ]
  }
}
```

4.2 SYSTEM INTEGRATION

Spray recommendations are the focus of SAS Pro structure and user interface. This characteristic made possible a complete scenario assessment for strawberry growers, where spray events need to be registered in the app to dismiss field alerts. Thereupon spray restrictions can be generated and help educate users on their disease control strategies and pesticide use while also minimizing risks of resistance development.

The data presented on Table 5 was extracted from AgroClimate Database (AD) as a visual reference of common interactions between the developed system and users.

Table 5. SAS Pro: Season Events extracted from AgroClimate Database.

DATE	EVENT TYPE	ACTOR	DESCRIPTION
Feb 05 06:15PM	Disease Simulation	Models	Moderate Risk - Anthracnose iIndex: 0.27 | Botrytis iIndex: 0.61
Feb 05 06:25PM	Spray Recommendation	SRDT	Spray Fungicide
Feb 05 06:30PM	Disease Simulation	Models	High Risk - Anthracnose iIndex: 0.84 | Botrytis iIndex: 0.99
Feb 05 06:40PM	Answer Questionnaire	SRDT	Is Current Peak of Bloom?
Feb 07 09:55AM	Questionnaire Answered	User	Peak of Bloom Set to True
Feb 07 09:55AM	Spray Recommendation	SRDT	Spray Fungicide
Feb 08 07:05AM	Spraying	User	Fungicide Application
Feb 08 07:05AM	Spray Restrictions	SRDT	Restrictions Generated
Feb 08 07:05AM	Spray Recommendation	SRDT	No Spray Needed - Protected by Fungicide Application

The interactions presented on Table 5 follows a set of specific required actions from the user, such as spraying and crop condition reports. Although these specific requirements can create certain levels of use resistance. We believe it can also promote a broader acknowledgment of current issues related to pesticide use in specialty crops. This approach also helps to better translate real on-site conditions by sustaining spray recommendations until an action is reported in the system, which can be overlooked in tools that only present disease risks without keeping track of field protection.

Another interesting example of this integration between disease risk, spray recommendations, and restrictions can be observed in product recommendations that exclude fungicides of groups which are currently restricted due to use limits being reached, as presented on Figure 30.

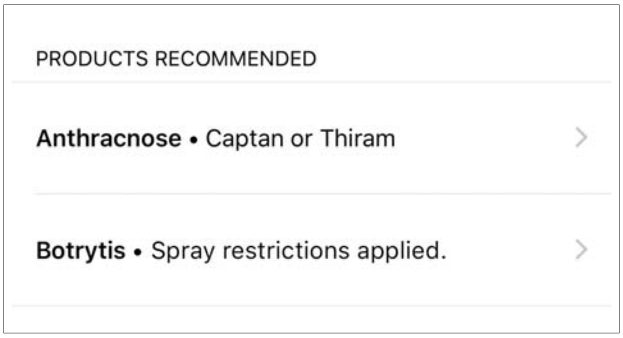


Figure 30. SAS Pro: Fungicide excluded from recommendation due to active group restrictions.

4.3 USABILITY

The crescent use of mobile apps in agriculture is closely linked to the on-site, real-time nature on which operational farming decisions are made, what is generally a good fit for use of portable devices. To achieve a satisfactory solution in agriculture-related apps, user interface and experience disciplines need to be considered.

Complex systems can easily increase the number of features and setup process in a mobile solution. This was one of the challenges during the development of SAS Pro, specially considering the use of generic database and services that provide a back-end structure to other agriculture apps under the AgroClimate project.

SAS Pro interface is highly focused on the main subject of a giving feature on different screens. Complementary information is presented with secondary preeminence. Two main examples of this technique are:

(a) **Fields List**: In the main screen of the app, bold larger text is used to identify fields, but grouping of such fields follows a priority order described in each section (Figure 31) of the table with different urgency-matching colors, in the following order: ***Spray Fungicide***, ***Answer Questionnaire***, ***No Disease Simulation***, and lastly ***No Spray Needed***.

This prioritized grouping allows users to focus its attention in the initial items of the table, if a field have a spray fungicide action recommended, then it will be listed on the top of the screen, minimizing the risk of being overlooked and reinforcing the importance of such recommendations.

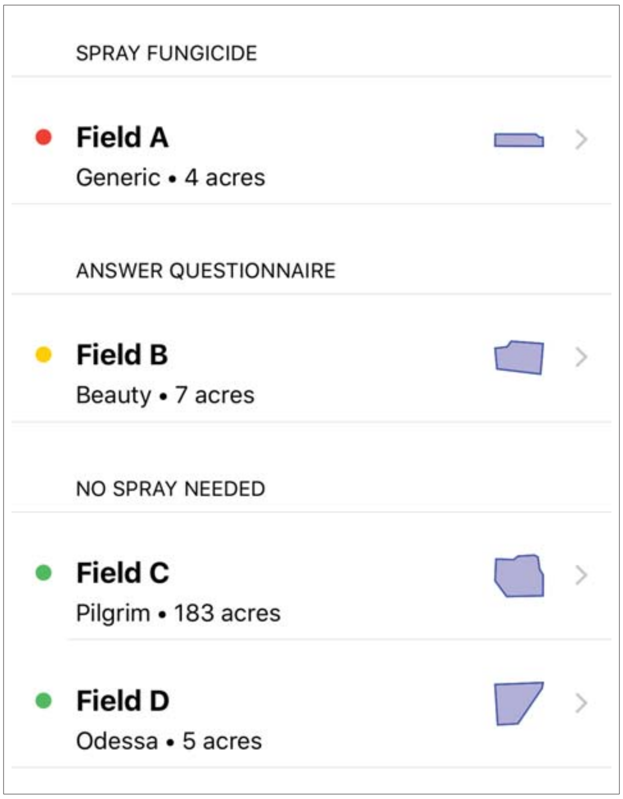


Figure 31. SAS Pro: Fields list grouped by action provides a priority-focused visual reference to users.

(b) **Detailed Recommendation**: When selecting a field in the main screen, a detailed recommendation screen is presented. With the spray action and its matching color in the top of the screen, a brief but necessary recommendation explanation follows. The mid part of the screen is reserved for products recommendations, if existent. While the bottom part is reserved to actions and additional features available, such as, spray restrictions, weather conditions and infection risks forecast.

This position and size hierarchy provides an easier assessment of the presented information. In the explanatory recommendation text, words representing risks and diseases use bold typography (Figure 32) hinting to further simulation data when selected, where users can confirm information about observed infection risks.

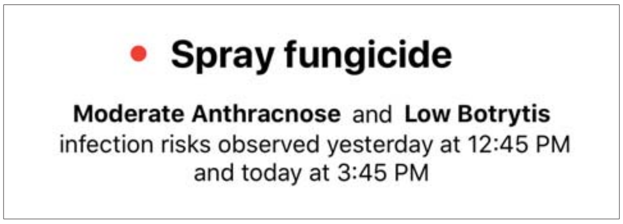


Figure 32. SAS Pro: Highlighted diseases and risks indicating further data access.

Interaction feedback and supplementary visual reference are also important aspects for a better mobile user experience. On SAS Pro Disease Simulation graph interface, an interaction feedback is used when users are scrolling through simulated data of a specific disease. Users can simply tap a particular region of the graph to check the maximum infection index observed in that day. Panning gestures are also supported to navigate between periods to check next and previous days values. When tapping or panning, a thin line serve as interaction feedback to inform the user what part of the graph he is reaching, as presented in Figure 33[22].

Figure 33. SAS Pro Disease Simulation Graph: Thin line serves as interaction feedback in a graph interface.

[22]The white circle on Figure 33 was added to represent the user touch and is not part of the interface.

5. CONCLUSIONS AND FUTURE WORK

Considering its built-in integration between disease models, spray recommendations, and resistance management guidelines, SAS Pro is a prominent support tool for disease control in strawberry production. It also provides an educational component where information on fungicide groups, mode of action and active ingredients are easily accessible within the mobile app.

Additionally, strawberry growers are alerted about active spray restrictions on a field level. New spray strategies can be reviewed within the app contributing to a more effective product rotation throughout the season, reducing the risk of resistance development on target pathogens.

SAS Pro focus on spray recommendations contributes to a more realistic view of a field condition by keeping track of disease simulation indexes and protective sprays. Users have access to detailed information about a recommendation which helps them address when a specific disease risk was observed or which fungicide application is protecting a given field, despite of recent infection risks observed.

As future work, further app evaluation during the 2018/2019 strawberry season in Florida, USA, will be performed and include a version for the Android operating system. Improvements on the services for faster data retrieval are also planned along with other suggestions from a recent meeting with growers and project members that include:

(a) Addition of a map-based view with infections indexes of all supported weather stations.

(b) Display last spray event of each field, in the main screen.

(c) Support to multiple users with access permissions.

(d) Data synchronization between local and server database.

Another feature that is being studied for future implementation is the support to interactive notifications, a framework supported from iOS 10 and Android 7.0 (API level 24) and superior. Which would allow users to execute actions and receive results directly from the notification interface, without the need to open the app to perform these changes. This feature would be specially useful when information from the users is required to generate a spray recommendation.

The development of the Strawberry Advisory System Pro (SAS Pro) was funded by the Florida Strawberry Research and Education Foundation (FSREF). Southeastern USA is a prime location for the implementation and testing of disease risk and fungicide resistance tools due to the need for continuous disease control associated with warm and humid climates. Testing for region specific recommendations and restrictions are required for future expansion of the system to other states. Production versions are expected to be available to the general public in the beginning of the 2018/2019 strawberry season in Florida, USA.

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ATTACHMENT A – FUNGICIDES USED ON STRAWBERRY PRODUCTION

Fungicides used on strawberry production for control of Anthracnose and Botrytis ordered by disease and FRAC group according to their mode of action.

Disease (Pathogens)	Fungicide Group	Chemicals (Active ingredients)	Max. Rate/Acre		Min. Days to		Remarks
			Appl.	Season	Harvest	Reentry	
Anthracnose Fruit Rot (Colletotrichum acutatum)	**M4**	Captan 50W	**See individual labels**		1	1	Rate per treated acre. Special label for FL allows up to 24 applications per season.
		Captan 50 WP					
		Captan 80 WDG					
		Captan 4L					
		(captan)					
	M4 + 17	Captevate 68 WDG	5.25 lb	21 lb	0	1	Do not make more than 2 consecutive applications.
		(captan + fenhexamid)					
	1 + 3	Protocol	1.33 pt	5.3 pt	1	1	Do not make more than 2 consecutive applications before rotating to another fungicide with a different mode of action.
		(thiophanate-methyl + propiconazole)					
	3	(propiconazole)	4 fl oz	16 fl oz	0	0.5	Do not make more than 2 consecutive applications.
		Amide, Propico-nazole EC, Bumper 41.8 EC, Fitness, Orbit, Propi-Star EC, Shar-Shield, PPZ, Tilt, Topaz.					
	3 + 11	Quadris Top	14 fl oz	56 fl oz	0	0.5	Do not make more than 2 sequencial applications before alternating to another fungicide group and no more than 4 appl/crop per year.
		(difenoconazole + azoxystrobin)					

	3 + 11	Quilt Xcel	14 oz	56 oz	0	0.5	Do not make more than 2 consecutive applications and no more than 4 appl/crop.
		(azoxystrobin + propiconazole)					
	9 + 12	Switch 62.5 WG	14 oz	56 oz	0	0.5	Do not make more than 2 consecutive appl. Do not plant crops not on the label, for 30 days after last app. See special label for instructions on dipping transplants
		(cyprodinil + fludioxonil)					
	11	Abound, Aframe, Azaka, Azoxy 2SC, Equation, SC, Satori, Trevo	15.4 fl oz	1.92 qt	0	4hr	Do not make more than 2 sequential appl. and no more than 4 appl/crop year. See label for instructions on dipping transplants.
		(azoxystrobin)					
	11	Cabrio EG	14 fl oz	70 fl oz	0	0.5	Do not make more than 2 sequential applications and no more than 5 appl/crop per year.
		(pyraclostrobin)					
	11	Flint	3.2 oz	19.2 oz	0	0.5	Do not apply more than 2 sequential applications of Flint and other Group 11 fungicides. Do not exceed more than 6 total applications of Group 11 fungicides per season.
		(trifloxystrobin)					

	11	Aftershock	5.7 fl oz	22.8 fl oz	1	0.5	Do not make more than 2 sequential applications and no more than 4 applications per season. Minimum interval of 14 days between applications
		Evito					
		(fluoxastrobin)					
	11 + 7	Merivon	11 fl oz	33 fl oz	0	12 hr	Do not make more than 2 sequential applications before alternating to a another non-Group 7 or non-Group 11 fungicide.
		(pyraclostrobin + fluxapyroxad)					
	11 + 7	Pristine	23 oz	115 oz	0	0.5	Do not make more than 2 consecutive appl. and no more than 5 appl/ crop.
		(pyraclostrobin + boscalid)					
	11 + 7	Luna Sensation	7.6 fl oz	27.3 fl oz	0	0.5	Do not make more than 2 sequential applications before rotating with a fungicide from a different group.
		(tryfloxystrobin + fluopyram)					
	19	Affirm WDG, Ph-D, Oso, Veranda O	**See individual labels**		0	4 hr	Use in alternation with fungicides that have different modes of action. Do not make more than 3 applications per season.
		(polyoxin-D)					
Botrytis Fruit Rot (Botrytis cinerea)	**M3**	Thiram, Granule, Thiram 24/7	**See individual labels**			1	Do not rotate treated crops with other crops for which Thiram is not

		(thiram)					registered.
	M4	(captan)	**See individual labels**		1	1	Rate per treated acre. Special label for FL allows up to 24 applications per season.
		Captan 50W, Captan 50 WP, Captan 80 WDG, Captec 4L					
	M4 + 17	Captevate 68 WDG	5.25 lb	21 lb	0	1	Do not make more than 2 consecutive applications.
		(captan + fenhexamid)					
	M12	Fracture	36.6 fl oz	183 fl oz	1	4 hr	Do not,make more than 2 sequential applications.
		(banda de lupins albus doce - BLAD)					
	1	(thiophanate-methyl)	**See individual labels**		1	1	Fungicides from different chemical groups should be used in spray program for disease resistance management.
		Thiophanate-methyl 85 WDG, Topsin 4.5 FL, Topsin 70 WDG, Topsin,M 70 WP, Topsin M WSB, Incognito 4.5F, Cercobin, Nufarm T-Methyl 4.5 F, Nufarm T-Methyl 70WSB					
	1 + 3	Protocol	1.33 pt	5.3 pt	1	1	Do not make more than 2 consecutive applications before rotating to another fungicide with a different mode of action.
		(thiophanate-methyl + propiconazole)					
	2	(iprodione)	2 pt	2 pt	N/A	1	Do not make more than 1 application per

		Enclosure 4, Iprodione 4L AG, Meteor, Nevado 4F, Rovral 4 Flowable					season. Do not apply after first fruiting flower.
	7	Fontelis	24 fl oz	72 fl oz	0	0.5	Do not make more than 2 sequencial applications before alternating to a fungicide from a different group.
		(penthiopyrad)					
	7	Kenja 400 SC	15.5 fl oz	54 fl oz	0	0.5	Do not plant other crops not registered within 30 days after last application.
		(isofetamid)					
	7 + 9	Luna Tranquility	27 fl oz	54.7 fl oz	1	0.5	Do not make more than 2 sequential applications before rotating with a fungicide from a different group.
		(fluopyram + pyrimethanil)					
	7 + 11	Luna Sensation	7.6 fl oz	27.3 fl oz	0	0.5	Do not make more than 2 sequential applications before rotating with a fungicide from a different group.
		(fluopyram + tryfloxystrobin)					
	7 + 11	Merivon	11 fl oz	33 fl oz	0	12 hr	Do not make more than 2 sequential applications before alternating to a another non-Group 7 or non-Group 11 fungicide
		(fluxapyroxad + pyraclostrobin)					
	7 + 11	Pristine	23 oz	115 oz	0	0.5	Do not make more than 2 consecutive appl.

		(boscalid + pyraclostrobin)					and no more than 5 appl/crop.
	9	Scala SC	18 fl oz	54 fl oz	1	0.5	Do not make more than 2 consecutive applications. Do not use more than 2 of 6 appl. in any one season
		(pyrimethanil)					
	9 + 12	Switch 62.5 WG	14 oz	56 oz	0	0.5	Do not make more than 2 consecutive appl. Do not plant crops not on the label for 30 days after last app. See special label for instructions on dipping transplants.
		(cyprodinil + fludioxonil)					
	17	Elevate 50 WDG	1.5 lb	6 lb	0	0.5	Do not make more than 2 consecutive applications.
		(fenhexamid)					
	19	Affirm,WDG, Ph-D, Oso, Veranda O	**See individual labels**		0	4hr	Use in alternation with fungicides that have different modes of action. Do not make more than 3 applications per season.
		(polyoxin-D)					
Botrytis (suppression only)	**11**	Abound, Aframe, Azaka, Azoxy 2SC, Equation SC, Satori, Trevo	15.4 fl oz	1.92 qt	0	4 hr	Do not make more than 2 sequential appl. and no more than 4 appl/crop year. See label for instructions on dipping transplants.
		(azoxystrobin)					

	11	Cabrio EG	14 fl oz	70 fl oz	0	0.5	Do not make more than 2 sequential applications and no more than 5 appl/crop year.
		(pyraclostrobin)					
	11	Aftershock	5.7 fl oz	22.8 fl oz	1	0.5	Do not make more than 2 sequential applications and no more than 4 applications per season. Minimum interval of 14 days between applications.
		Evito					
		(fluoxastrobin)					