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DRONE TECHNOLOGY: IS IT WORTH THE INVESTMENT IN AGRICULTURE

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DRONE TECHNOLOGY:
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By

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DRONE TECHNOLOGY: IS IT WORTH THE INVESTMENT IN AGRICULTURE

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From the earliest of times, the human race has sought to better understand this world and its surroundings. In the last century, aeronautical engineering and aerial imagery have evolved to allow a deeper understanding into how this world lives and breathes. Now more than ever, these two technological advancements are changing the way we view this world and how we are to sustain it for a brighter, healthier future.

Over time, the advances of these two technologies were combined and the birth of spectral sensing and drone technology arrived. In their earliest years, drones and spectral imaging were only available to government agencies. In the mid-1990s, President Clinton declassified this technology and allowed the public to utilize and invest in their development.

Today, the world has incorporated these technologies into a number of applications; one of these being in agriculture. In the last decade, significant interest into drone technology and its possible applications have been researched. Many benefits have been discovered in the agricultural sector by incorporating drone and spectral technology. A big part of incorporating a new piece of equipment or technology into any operation is the economic feasibility. Understanding drone and spectral technology can do and what it can provide, is crucial in making a sound decision when considering investing in drone technology.

This document discusses the earliest developments of drone technology, its current status, and the predicted future. It also provides basic information about drone designs, drone regulations, types of spectral sensors, their capabilities, and some of the research being done in agriculture to advance these technologies. Additionally, a case study looking at a wild oat infestation in spring wheat will be addressed. This case study involves two crop consultants and their decision to invest in drone technology.

DEDICATION

I dedicate the work of this document to my wife, children, and posterity. Additionally, I dedicate this to my great grandmother, Opal Ann Jenson Naylor, whose final mortal words to me were: “Do well in school.” Through the love and support of my family, close friends, and the words of my great grandmother, I was able to find the strength, energy, and endurance needed to complete this document and my doctoral degree.

If there’s only one thing to take away from this document, let it be this: That with God and family at your side, things that once seemed impossible can become a reality.

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CHAPTER 1

A BRIEF INTRODUCTION TO AERONOTICS, AERIAL IMAGING, AND THE EARLY DEVELOPEMT OF DRONES

Introduction

From the beginning of time, *Homo sapiens* have looked skyward in amazement and wonder. The feeling of grandeur and hope has driven the human race to achieve what seemed to be the unattainable. For centuries, we as a species have looked to the skies and heavens in hope that a better understanding of the world around us would be delivered. Yearning for understanding led many astronomers, physicists, engineers, and other scientists to theorize the composition of this universe. People like Nicolaus Copernicus, Galileo, Aristotle, Leonardo da Vinci, and Sir Isaac Newton all sought after universal truth. This yearning didn’t stop with these well-known philosophers hundreds of years ago; it also led to developments by a French inventor and two brothers that transformed the world forever.

History & Development of Aerial Imagery

In the early 1820s, a French inventor by the name of Joseph Niepce took the first successful photograph. By the late 1830s, a business partner of Niepce created the daguerreotype image method, which used silver-plated copper and mercury vapor to produce a photograph (Daguerrobase, 2019). This was the primary method of photography for nearly 30 years (Daguerrobase, 2019). Since then, photography has seen some outstanding evolutionary developments. Today, nearly every human being on the face of the earth has had their photograph taken or has the capability to take a picture whenever or wherever they are located. Photography has truly changed the world in which we see it, but it was an outstanding achievement over gravity and physics nearly 80 years later that truly helped revolutionize photography.

On December 3, 1903 in Kitty Hawk, North Carolina, two brothers, Orville and Wilbur Wright, successfully created the first powered, heavier-than-air machine, and achieved sustained flight with a pilot aboard (Biography, 2014).

Once the Wright brothers successfully took to the skies, a forced marriage with photography seemed imminent. The first known aerial photograph was taken in 1858 by French photographer and balloonist, Gaspar Felix Tournachon (Baumann, 2014). With the invention of powered flight now in the mix, aerial photography from an airplane quickly followed. A few short years after the flight at Kitty Hawk, a photographer named L.P. Bonvillian took to the skies to take the first photograph from an airplane, with the pilot being none other than Wilbur Wright himself (Madeira and Green, 2016). With the successful marriage of aeronautics and photography in place, the human race began to utilize these two innovations even more. This led to increased technological advancements in both aeronautics and photography.

Between the years of 1907 and 1930 numerous aircraft companies came into existence in the United States. Many of these founders' companies are still in business today (Lopez, 1995):

- Glenn Curtiss in 1907- Curtiss
- Glenn Martin in 1912- Martin Marietta
- William Boeing in 1916- Boeing
- Donald Douglas in 1920- McDonnel Douglas
- Alan Lockheed in 1926- Lockheed-Martin
- John Northrop in 1929- Northrop
- Leroy Grumman in 1929- Northrop Grumman

Other aircraft companies started to pop up in other countries as well. Germany, France, and the UK all became major players in the aircraft business. In 1939, aeronautic technology and aerial imagery would soon impact the lives of millions of people. It would became a matter of life and death.

World War II began in 1939 when Germany invaded Poland in 1939. Even though aircraft and aerial photography saw its awakening in the First World War, this war in particular would push the development of aircraft and aerial imagery to an entirely new level. General Werner von Fritsch, Chief of the German General Staff, made a prophetic statement: “The nation with the best photo-reconnaissance will win the war” (Fischer, 1975). General Fritsch’s prophetic statement continued to ring true in every world conflict since.

Desperate times of war accelerated the advancement and understanding of how photography could be clearly captured from higher altitudes and speeds. As time progressed, billions of dollars had been spent on aeronautical engineering and aerial imaging capabilities. In 1954, President Dwight Eisenhower approved the U-2 aerial reconnaissance program (Brugioni and Doyle, 1997). In cooperation with th U.S. Air Force, Eisenhower instructed the CIA to contract with Lockheed to develop a photo-reconnaissance jet aircraft that could fly above the Soviet Union (now Russia) to photograph and document their military capability. The first U-2 aircraft ready for reconnaissance was ready by

Figure 1. U-2 aircraft in flight
Photo Credit: U.S. Air Force
www.af.mil

1956 (Rich and Janos, 1994). The U-2 aircraft (Figure 1) was able to fly at an altitude of 70,000 feet and was equipped with a new type of camera. The new camera had a resolution of 2.5 feet (76 cm) from an altitude of 60,000 feet (18,000 m) (Petrescu and Petrescu, 2013). This advancement in camera technology and resolution made it possible to capture images with a high enough resolution that buildings, factories, cars, trucks, and military installments could be more easily identified.

Figure 2. SR-71 in flight (top), and park on the tarmac (bottom)
Photo Credit: NASA

The U-2 program opened the door to a new century of aerial imagery, aeronautics, and the development of new technologies. Unfortunately, the boom these technological advancements saw always seemed to follow the trend of world conflict. By the 1960s the U-2 aircraft and its technology needed desperate updating. With the development of better radar devices and defensive missiles, the U-2’s dauntingly slow speed became problematic (Lockheed Martin, 2019).

Lockheed was put to the task again, developing an aircraft with the sole purpose of aerial imagery and reconnaissance. In 1965, Lockheed delivered the SR-71 to the United States Air Force (Figure 2). Unlike the U-2 aircraft, the SR-71 could fly at an altitude of 85,000 feet and at a mind-crushing speed of over 2,300 m.p.h. (3,704 kmph). In 1976, the SR-71 set the world speed and altitude records of 2,193 m.p.h. at 85,126 feet. This aircraft had only one payload and always one mission, to carry a camera and to take aerial reconnaissance images (Gibbs, 2015).

During the development of the U-2 and the SR-71, satellite technology was in major development. The first unmanned satellite to orbit the earth was *Sputnik I*, launched by the Soviet Union on October 24, 1957. The launching of *Sputnik I* confirmed a worldwide “open skies” policy for objects launched into orbit (ESOA, 2016). The United States quickly initiated the Corona orbital satellite reconnaissance program, and by 1959 launch operations began (Figure 3). This program was managed by the United States Air Force and the CIA. The main purpose of the Corona program was aerial imagery and reconnaissance (McDonald, 1997b).

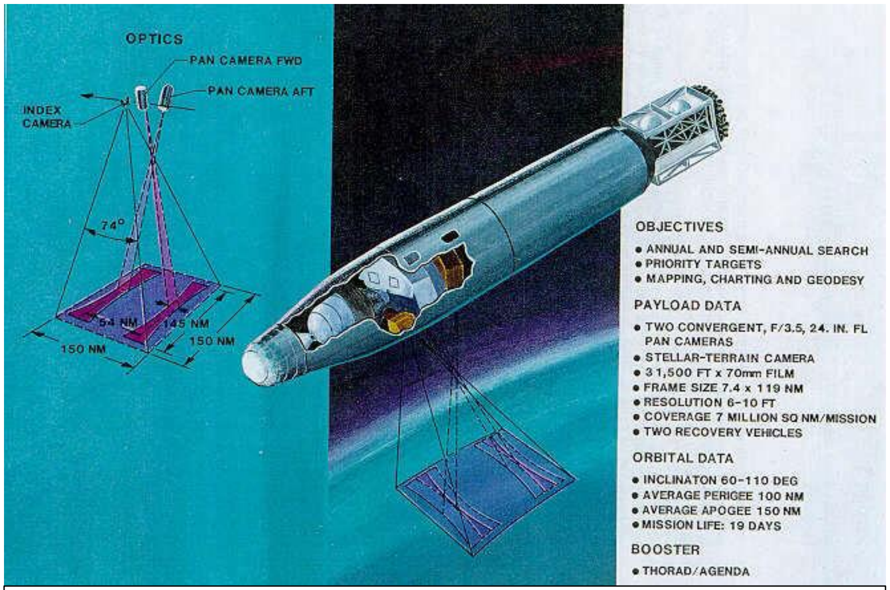

Figure 3. Detailed image of the Corona satellite.
(Modified from Wikimedia Commons, 2005)
File name: Kh-4b_Corona.jpg

In 1960, a successful Corona reconnaissance mission was finally accomplished. Mission 9009 became the first Corona satellite to be launched into orbit and successfully recovered back on earth (McDonald, 1997a). In just one mission, the Corona satellite provided more photographic coverage of the Soviet Union than all previous U-2 missions. The success of the Corona mission ushered in additional funding and further developments of satellite-based imagery.

In 1967, President Lyndon Johnson said this about investing in satellite-based imagery: “We’ve spent thirty-five to forty billion dollars on the space program. And if nothing else had come out of it except the knowledge we’ve gained from space photography, it would be worth ten times what the whole program has cost” (Richelson, 1992). Today we now know that the images acquired from the Corona program helped update local and foreign maps and brought needed intelligence during other world conflicts.

Since the Corona program, the United States and a handful of other countries have invested heavily into satellite technology and imagery. Much of this investment has continued to go towards aerial reconnaissance and intelligence, but a significant portion is now being spent on georeferencing, remote sensing, and multispectral technology. Satellite platforms like Landsat, IKONOS, Galileo, GLONASS, NAVSTAR, and Global Navigation Satellite Systems (GNSS) were all launched into orbit from 1972 to 1999. Today, newer and updated platforms for these satellites are being used (Landsat, 2019).

The launching of these satellite platforms brought a new wave of military aircraft. With the support of the GNSS platform, aircraft could now be remotely connected and guided with precise accuracy across the globe. In the 1980s the Department of Defense (DOD) invested billions of dollars in the development of unmanned aerial vehicles (UAVs) (Jensen, 2007). These UAVs started to become extremely popular in the United States military (Staff, 2018). UAVs are lightweight, can fly at high altitudes, have a long flight time, and can carry cameras or weapons. Additionally, if a UAV crashes or gets shot down, no physical pilot is on board. These UAVs saw their biggest spike of use in 2010 when the United States was fighting wars in the Afghanistan and Iraq. UAVs were being used on diverse platforms. Such diversity included collecting aerial reconnaissance imagery or providing offensive and defensive support to ground troops (Naylor and Luce, 2018).

At first, the satellite platforms and guidance systems that made UAVs so versatile were only accessible by the military, but in 1995 that changed. On February 22, 1995, President William Clinton signed Executive Order Number 12951, which stated: “The release of certain scientifically or environmentally useful imagery acquired by space-based national intelligence reconnaissance systems to be declassified. Such imagery shall be deemed declassified and shall be made available to the public” (The White House, 1995). The signing of the executive order made it possible for other government and private entities to use and further invest in satellite technology. Due to this executive order, the advancements technology would see in the next two decades would forever change the way the human race viewed and captured the world around them.

Shortly after the executive order was declared, companies like Garmin, Keyhole Inc. (Now Google Earth), TomTom, Lowrance, Boeing, Lockheed Martin, Yuneec, and Da-Jiang Innovations (DJI) began competing to produce this technology for public use (Wikipedia, 2019). Companies like Garmin, TomTom, and Lowrance created many products available for public use that utilized Global Positioning Systems (GPS) (History of Garmin, 2004). These products were able to determine the latitude and longitude of a receiver on Earth by calculating the time difference of signals from different satellites to reach the receiver. This process happens at the speed of light and its outcome generates extreme precision (NASA, 2015). Even though GPS technology was nothing new, developing a product that was affordable to the public market was. GPS technology and devices started to appear everywhere (Sturdevant, 2015). Handheld devices, automobiles, and airplanes all started to utilize GPS technology more fully.

With Global Positioning Systems now available for public use, some companies started to utilize GPS and radio wave technology. The U.S. military had already put these two technologies together and created the unmanned aerial vehicle (UAV) in the 1980s. Now it was time for the public sector to incorporate the two. These small UAVs were quickly named drones by the public. Drones utilized GPS and remote control technology. As UAV technology improved in the military sector, those same technological improvements could now be implemented into drones in the public sector as well.

Non-military drone use started to appear around 2006. Government agencies used drones for disaster relief, border surveillance, and for fighting wildfires (American Red Cross, 2015). Corporations began using drones to inspect powerlines, pipelines, and agricultural land for better management practices (Workswell, 2018).

Through the last decade, drone interest and technology has skyrocketed. Between 2006 and 2014, an average of two commercial drone permits were issued by the Federal Aviation Administration (FAA) every year. This number jumped to 1,000 permits in 2015. The following year, 2016, this number tripled to 3,100 commercial drone permits (Dronethusiast, 2018). As the technology got better and cheaper, public interest increased and drone technology became a hot commodity.

A Decade of Drone Advancements

In the last decade, drone technology, design, and versatility have evolved drastically. With technological advancements like the internet, Wi-Fi, and Bluetooth, drone versatility changed rapidly. Wi-Fi and Bluetooth technology made flying a drone and accessing real time imagery extremely easy and user friendly. In the early 2000s, many drones had three basic designs:

- Octocopter (8 propellers)
- Quadcopter (4 propellers)
- Fixed-wing (Flying wing with 1 to 2 propellers)

Drones consisting of all three designs relied mostly on line-of-site flight navigation. Line-of-site flight relies heavily on pilot input and operation. This can become very challenging when facing different kinds of terrain, weather, and obstacles. With the advancement of Wi-Fi and GPS technology, a drone pilot could now receive a real time video and location feed while in flight. This allowed a drone operator the capability to fly over, around, and even through difficult obstacles. It also allowed for higher altitudes and longer distances for drone operation.

During this same time, portable cellular devices were also evolving. Cellular phones, digital portable tablets and iPads also incorporated the Wi-Fi and Bluetooth technology. In January 2007, Apple launched its first iPhone. The company described the phone as combining three products into one handheld device: a mobile phone, an iPod, and a wireless communication device (CBS News, 2013). One of the original iPhone's more revolutionary features was that it allowed users to command the device using only their fingers on a touch screen. This technology made drone technology even more desirable to the public. With the ability to connect a personal device to a drone controller and video receiver, drone technology became very user friendly.

Drones soon entered a new world, one that was not solely based on military or humanitarian use. Instead, drones were now being used in architecture and engineering, geography, cartography, law enforcement, real-estate, urban planning, plant and wildlife conservation, and agriculture.

Vocational compatibility of drones was being tested in all kinds of applications. One such integration came from the University of Nebraska-Lincoln (UNL). In 2016 UNL researchers Carrick Detweiler and Sebastian Elbaum created what they called the “Fire Drone” (Figure 4). This particular drone was created and engineered to assist in fighting wild fires. The Fire Drone project began two years prior (2014) as a new way to prevent wildfires in Nebraska and other western states. The idea of creating a Fire Drone was conceptualized after a severe drought in 2012. During that drought year, Nebraska saw

Figure 4. A “Fire Drone” returns to be reloaded with incendiary plastic spheres after dropping a payload during a prescribed burn at the Homestead National Monument of America
Photo Credit: Craig Chandler / University Communications

1,570 wildfires that burned a total of 786 square miles; an expanse nearly seven times the size of Omaha, Nebraska's largest populated city. The combined costs of ground-level firefighting, aerial suppression and assistance from other states cost Nebraska more than $11 million that year (Koperski, 2016).

The Fire Drone was created by the university's Nebraska Intelligent Mobile Unmanned Systems Laboratory (NIMBUS). It carried up to 13 fire balls and has the capability to carry a little more than one pound of cargo. UNL researchers and the Nebraska Forest Service hoped the technology could eventually be used to set controlled fires in hard-to-reach places that would clear out brush and small trees and make it more difficult for wildfires to sweep through an area (Koperski, 2016).

With the development of the Fire Drone, fire fighters could now prevent and fight wild fires a little more safely. Safety and security is an area drone technology has seen major promise in. One particular example comes from the Liwonde National Park in Africa. In 2016 and 2017, drones were being deployed to combat the poaching of African animals. Africa is in the midst of a profound poaching crisis: "The continent's elephant population declined by 30 percent from 2007 to 2014, much of which is a result of poaching. At least 1,338 rhinos were killed for their horns in 2015 alone. Criminals are becoming increasingly militarized in their tactics, and efforts to stop them have had little success" (Nuwer, 2017).

Due to this animal safety crisis, the African Parks Department turned their eyes skyward for help. With funding from the World Wildlife Foundation and Google, drones began to be tested for their potential to combat the poaching crisis. The drones were outfitted with thermal and night vision cameras, video transmitters and telemetry, and with battery changes, could stay in the air for the entire night. This program is the first systemic evolution of a drones' potential to combat poachers in Africa and to protect many unique African natural resources (Nuwer, 2017).

These are only a few examples of how technology and President Clinton's Executive Order has revolutionized aerial imaging and drone technology in the last decade. Many more diverse approaches to drone technology are being tested. In the last ten years, drone capabilities have changed as well. The size, shape, weight, flight time and payload capacity of drones has evolved. The first military UAVs weighed anywhere from fifty pounds to twenty thousand pounds (DOD and NASA, 2005). Drones in the last decade typically have weighed less than fifty pounds and as small as 1.1 ounces (32 grams) (FAA, 2017).

Types of Drones

Fixed-wing Design

Even though drone technology and aerial imagery has evolved substantially in the last two decades, the design and aeronautical components have remained nearly the same since the creation of UAVs. As briefly discussed earlier in this chapter, three major designs types are currently being used for drones.

The oldest design can be dated back to the 1840s. A fixed-wing glider design was first put to the test in 1849 by Sir George Cayley (Crouch, 2018). This design was pivotal for all future aircraft. The Wright brothers acknowledged the importance of this design in the development of their creation of an aircraft (Velazquez, 2016). The fixed-wing configuration (Figure 5) utilizes the relationship of a typical wing design and aerodynamic lift (Figure 6).

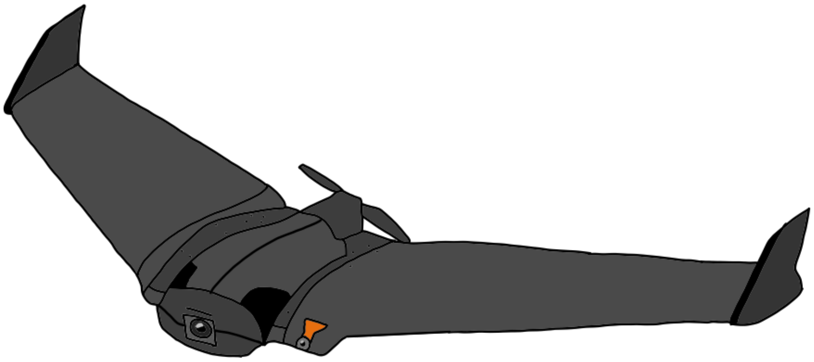

Figure 5. Fixed-wing drone design

Aerodynamic lift is an important concept to understand when talking about drone design and flight. No matter the design and shape of a drone, aerodynamic lift is utilized in one way or another. Wind blowing above and below a wing will cause the wing to achieve aerodynamic lift, as long as the wing is shaped properly. A flat wing shape fights airflow, causing drag (resistance), while a curved wing shape allows air to flow smoothly around it. A wing that is curved on the top and almost flattens out on the bottom creates aerodynamic lift. The molecules of air passing over the top of the wing surface have a longer distance to travel and therefore must move more rapidly, creating less pressure than the slower air flowing below the wing. The higher pressure of air below the wing exerts pressure upward, causing the wing

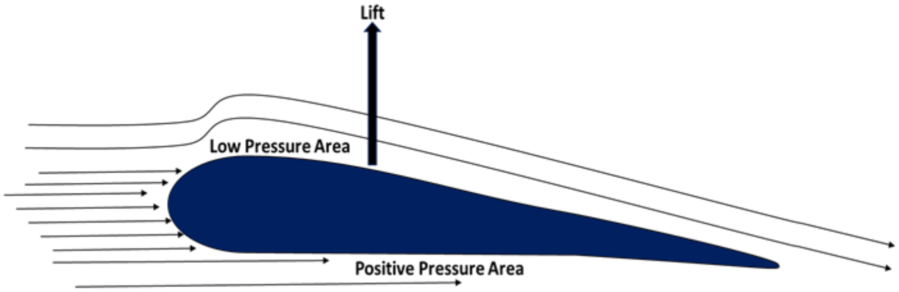

Figure 6. A Wing that is curved on the top and relatively flat on the bottom creates aerodynamic lift

to lift. Tilting the wing upward will increase the aerodynamic lift even more. However, if a wing is tilted too much in either direction, lift will be lost and the wing will stall and gravity will take over (Lopez, 1995).

A fixed-wing drone design is just that, the entire drone looks like a wing. The great thing about a fixed-wing design is that aerodynamic lift is generated over the entire drone. This makes the drone extremely aerodynamic and helps conserve valuable battery energy while in flight. Fixed-wing configurations typically have been the best at battery conservation which has resulted in the best flight times per battery than any other drone design. Fixed-wing drones like the AgEagle RAPID, PrecisionHawk Lancaster, and SenseFly eBee SQ are often preferred by growers because they can cover more area and spend more time in the air than a multi-rotor drone platform (Nixon, 2017).

Another benefit is the type of material one can use to build the fixed-wing design. Material like Styrofoam, polyurethane plastics, carbon fiber, and even woods like Spruce, Birch, and Fir have all been used in creating an aerodynamic wing (Light Aircraft Association LAA, 2008). Some of these materials are cheap, easy to find and manufacture. This tried and true design has been around for over 150 years. The fixed-wing drone configuration has been around longer than any other drone design. Unfortunately, this particular design has a few drawbacks, especially when considering drone capabilities in agriculture.

One of the biggest issues with drones right now is finding the balance between aerodynamics, payload, battery life, and practicality. Fixed-wing aircraft have a tendency to struggle in many of these areas. Once cameras, sensors, transmitters, and receivers are incorporated into the design, aerodynamics, payload, and practicality becomes an issue.

One way to combat these issues is by creating a larger wing design so all of the needed and wanted components of the drone can be easily placed. A larger wing and a heavier drone will require more power and thrust to generate that airflow. The way to generate additional airflow is with a bigger and more powerful battery. A more powerful battery is heavier and requires extra power to lift the drone. This relationship often contradicts itself and no benefits are gained.

One potential issue that fixed-wing designs face is landing safely after the desired flight is complete. Whether you’re using the drone in an agricultural or urban setting, a soft, safe landing zone isn’t likely. Fixed-wing drones do not have landing gear, meaning in order to return the drone back to its desired location a “crash landing” has to occur every single time. This becomes an issue because of the potential damage the camera, sensor, and drone can sustain. A long glide path and runway is needed for fixed-wing aircraft as well. These drones are best suited for large, open-field scanning (Nixon, 2017). As stated earlier, a big enough location to operate such a landing is minimal or nonexistent in many agricultural and urban settings. Damage to a drone and its components is something that must be taken seriously.

Expense is something that every individual and company has to keep in mind when considering investing in drone technology. Determining the size and design of the drone ultimately boils down to the desired task at hand. Fixed-wing aircraft have seen the most use in agriculture because this design is best suited for large scale, open-field sensing and imaging. Fixed-wing drones can carry a significant payload, resulting in more sensors and cameras on board while in flight. Due to this capability and extended versatility, the cost of fixed-wing drones generally is greater. The typical cost of a fixed-wing drone is $5,000 to $25,000 or more, after being fitted with sensors and cameras (Nixon, 2017).

Multi-Rotor Design

Unlike the fixed-wing drone design that uses aerodynamic lift in the form of a wing, the multi-rotor drone design uses multiple propellers to accomplish lift. In a lot of ways, a multi-rotor drone is much like a helicopter, but with some differences. The propeller blades of a helicopter are identical to the wings of an airplane or fixed-wing drone, when air is blown over them, lift is produced. The crucial difference between a fixed-wing and multi-rotor drone is that the flow of air is produced by rotating the propeller blades rather than moving the whole wing design forward (Krasner, 2012). Most multi-rotor drones will have four propellers. Some multi-rotor drones have six to eight propellers, but rarely more than that in their design.

Multi-rotor drones accomplish flight when the propeller blades spin fast enough to create aerodynamic lift. Unlike a helicopter, which pitches the propeller blade physically forward or backward to propel the helicopter in different directions (Figure 7), a multi-rotor drone speeds up or slows down its propeller blades

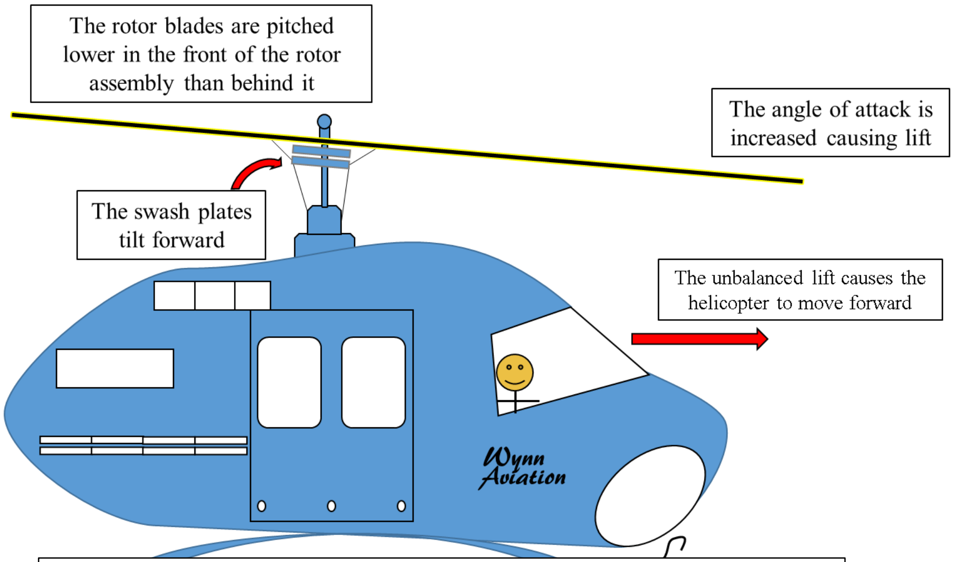

Figure 7. How a helicopter generates lift and aerodynamic

at the same time to accomplish directional flight. This way of flight is attainable because multi-rotor drones have an equal number of propeller blades spinning to the left and the right (Figure 8). If all propeller blades are spinning at the same angular velocity, level hovering flight is sustained. Whereas if any induced mismatched velocity occurs, directional and altitude flight is affected.

With the capability of vertical takeoff and landing, the multi-rotor design has become the front runner in the private sector. Due to its ability to hover while in flight, high resolution sensors and cameras can clearly capture extreme detail. A multi-rotor drone is a better choice for close-in scouting, spotting, and detailed surveying tasks than a fixed-wing drone (Nixon, 2017). Flying a multi-rotor drone, low and slow, gives you far more control over every image you shoot. As a result, accuracy and resolution are often better than what fixed-wing drones can deliver (Nixon, 2017).

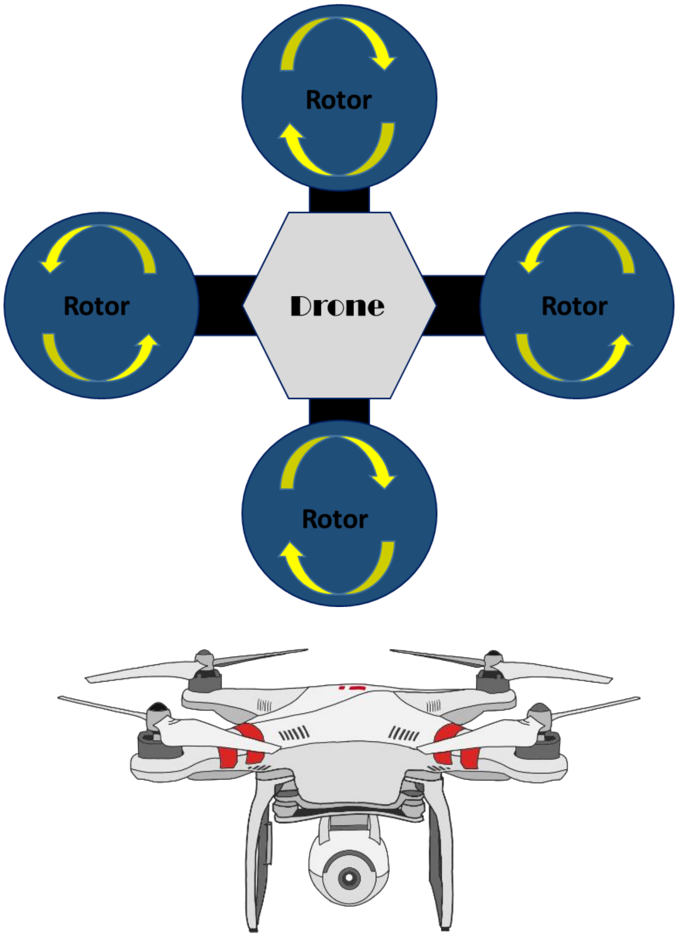

Figure 8. A multi-rotor drone hovers or adjusts its altitude by applying equal thrust to all four rotors

One of the major tradeoffs of using a multi-rotor drone versus a fixed-wing is far less range and coverage per flight. Many multi-rotor drones equipped for agricultural use, typically can only cover 50 to 100 acres (20 to 40 Hectares) of aerial imaging before a battery needs to be swapped out for a new one (Nixon, 2017). While battery changes are easy and user friendly, additional batteries for multi-rotor drones are necessary. This can became a major expense because many drone batteries will range in cost of $80 to $400 a piece. So depending on the target site size and how quickly you can charge a battery while *in situ*, will determine the number of batteries needed to accomplish the entire flight.

Multi-rotor drones are used in a vast number of tasks, from ranching, conservation, real estate, construction, and agriculture. The multi-rotor design is appealing because of its diverse capabilities with sensors and cameras. This remains especially true in agriculture. Growers and agriculture companies use a wide variety of sensors and the ability to install different brands and types of sensors onto one drone platform is extremely desirable.

Many agricultural drones do more than just take aerial images of a field. Most are equipped with some type of spectral sensor. Agricultural multi-rotor drones tend to be slightly cheaper than fixed-wing drones. Most “ready-to-fly” agriculture drones range from $1,500 to well over $25,000 (Nixon, 2017). Price tends to vary on the size and the capability of that particular drone.

Drone Popularity and the Need for Clearer Regulation

Stemming from the advancements of aerial imaging and drone technology, consumer interest and investment has increased in the last decade. Drones have become central to the functions of various businesses and governmental organizations and have managed to pierce through areas where certain industries were either stagnant or lagging behind (Joshi, 2017). The market for commercial and civilian drones will grow at a compound annual growth rate (CAGR) of 19% between 2015 and 2020, compared with 5% growth on the military side, according to BI Intelligence, Business Insider's premium research service (Joshi, 2017). At the end of the day, the impact of commercial drones could be $82 billion and a 100,000 job boost to the U.S. economy by 2025 (AUVSI, 2019).

With an increase in interest and investment from the public sector, safety concerns surrounding drone technology became a hot topic. Some have said that Amazon was to blame for such a sudden rush to buy into drone technology. Amazon CEO Jeff Bezos announced in December of 2013 that the company was considering using drones as a delivery method. Amazon's announcement further ignited the public's interest in drone technology. According to Business Insider and Statista, drone sales to dealers in the United States in 2013, the year Amazon made the announcement, was $44 million. The following year, 2014, that number quadrupled to $204 million in drone sales to dealers. Then in 2015, drone sales skyrocketed again to over $440 million (Dunn, 2017).

This rush to invest in drone technology resulted in many laws and regulations being broken and misunderstood by many. Drones were now starting to appear in private and federal airspace, and over heavily populated areas and arenas. In some instances, drones began colliding with aircraft, powerlines, people's homes and property. On a few occasions, private drones started to appear over secret military installments (Blake, 2017). In a blink of an eye, the private sector of drone technology went from a misunderstanding of airspace and regulation to an issue of national security.

Prior to 2016, being able to legally operate a commercial drone was often a time-consuming and expensive process. In order to operate a drone commercially, businesses seeking to operate a drone needed to apply and receive a Section 333 Exemption and Certificate of Waiver or Authorization (COA) from the FAA. What made drone regulation so tricky prior to 2016 is that for over 55 years, aircraft and their pilots had to be certified to operate in the National Airspace System (NAS). This became a major problem for drone operators. At the time, there were no rules, regulations, or procedures to certify either the aircraft (drone) or the pilots. In 2012, the FAA Modernization and Reform Act (FMRA) was passed by the United States Congress. This Reform mandated that the FAA provide a means to safely integrate small unmanned aerial systems (sUAS/drones) into the U.S. National Airspace System (NAS). Congress further directed the FAA to provide an interim means to approve select operators for commercial drone operations. The FAA met Congress' demands and created Section 333 Exemption. Operators in their Section 333 application had to provide operations and maintenance manuals for their intended drone operations. They had to show how the operations of their drone would maintain an equivalent or greater level of safety as to a certified manned aircraft. Obtaining a 333 Exemption and a COA was very difficult and expensive at that time. Many businesses hired lawyers to draft all of the paper work needed before submitting their application for review. Once the application was complete and submitted to the FAA, a prolonged waiting period occurred. According to the FAA in 2015, the applicant could expect a minimum of six months and up to a year before a decision was made.

A prolonged waiting period wasn’t the only issue the 333 Exemption created. While Section 333 granted some drones the needed requirement to operate in the National Airspace System, it also retained the requirement that an FAA airman certificate was required to operate the aircraft (drone). In other words, to operate a drone commercially, the drone operator needed to be an FAA licensed pilot. This requirement became a large stumbling block. Finding an available licensed pilot to fly and operate a drone was time consuming and expensive. According to the FAA, in 2017 there were an estimated 609,306 active certified pilots in the United States (Bensclair, 2018). Ultimately, unless a business already had a licensed pilot at their disposal, the 333 Exemption was nearly useless.

By 2016, another regulation reform was needed. In 2015, nearly half the drones being sold and flown were by hobbyists and private individuals and not by businesses for commercial use. By October 31, 2017, this percentage saw another drastic turn. The FAA reported that

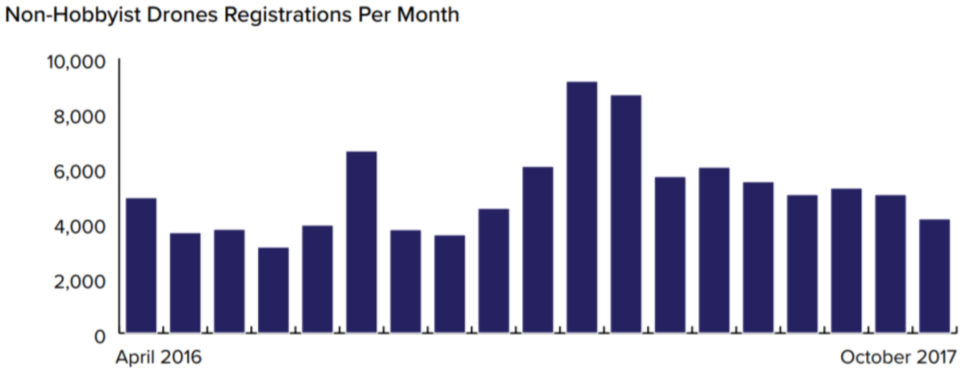

Figure 9. Growth of drone registration by Non-hobbyist in six months
Graph from: Gettinger & Michel, 2017

823,600 drones were registered to hobbyists (Figure 9) and 105,806 drones were registered for commercial non-hobbyist use (Gettinger & Michel, 2017).

This staggering number was important because under Section 333 Exemption, there was no mention of drone use for hobbyists. Section 333 outlined the rules and regulations for drone operation for commercial businesses and research but nothing further. This explosion of drone hobbyists generated a huge grey area in the current rules and regulations for drone operations.

The FAA faced a massive regulation nightmare. With thousands of drones being acquired every month, the FAA had to act quickly to address this issue of drone regulation and safety. In August of 2016, the FAA revised and compiled the new drone regulations. The revision was a new addition to the Title 14 Code of Federal Regulations (CFR). This revision and addition to the Federal Regulations was called Part 107.

Part 107 became the new standard for all small drone operations. These new regulations more clearly defined and outlined drone use for both hobbyists and commercial operators. The Operation and Certification of Small Unmanned Aircraft Systems in the Federal Register provided complete details and the following summary of the provisions of Part 107:

- Unmanned aircraft must weigh less than 55 lbs. (25 kg).
- Visual line-of-sight (VLOS) only
- At all times the small unmanned aircraft must remain close enough to the remote pilot in command and the person manipulating the flight controls of the small UAS for those people to be capable of seeing the aircraft with vision unaided by any device other than corrective lenses.
- Small unmanned aircraft may not operate over any persons not directly participating in the operation, not under a covered structure, and not inside a covered stationary vehicle.

- Daylight-only operations or civil twilight (30 minutes before official sunrise to 30 minutes after official sunset, local time) with appropriate anti-collision lighting.
- Must yield right of way to other aircraft.
- May use visual observer (VO) but not required.
- First-person view camera cannot satisfy “see-and-avoid” requirement but can be used as long as requirement is satisfied in other ways.
- Maximum groundspeed of 100 mph (87 knots).
- Maximum altitude of 400 feet above ground level (AGL) or, if higher than 400 feet AGL, remain within 400 feet of a structure.
- Minimum weather visibility of 3 miles from control station.
- Operations in Class B, C, D and E airspace are allowed with the required ATC permission.
- Operations in Class G airspace are allowed without ATC permission.
- No person may act as a remote pilot in command or VO for more than one unmanned aircraft operation at one time.
- No operations from a moving aircraft.
- No operations from a moving vehicle unless the operation is over a sparsely populated area.
- No careless or reckless operations.
- No carriage of hazardous materials.
- Requires preflight inspection by the remote pilot in command.
- A person may not operate a small unmanned aircraft if he or she knows or has reason to know of any physical or mental condition that would interfere with the safe operation of a small UAS.
- Foreign-registered small unmanned aircraft are allowed to operate under part 107 if they satisfy the requirements of part 375.
- External load operations are allowed if the object being carried by the unmanned aircraft is securely attached and does not adversely affect the flight characteristics or controllability of the aircraft.
- Transportation of property for compensation or hire allowed provided that—
  ○ The aircraft, including its attached systems, payload and cargo weigh less than 55 pounds total;
  ○ The flight is conducted within visual line of sight and not from a moving vehicle or aircraft; and
  ○ The flight occurs wholly within the bounds of a State and does not involve transport between (1) Hawaii and another place in Hawaii through airspace outside Hawaii; (2) the District of Columbia and another place in

the District of Columbia; or (3) a territory or possession of the United States and another place in the same territory or possession.

- Most of the restrictions discussed above are waivable if the applicant demonstrates that his or her operation can safely be conducted under the terms of a certificate of waiver.

Part 107 provided the guidelines needed to help move drone technology and the adoption of it forward. It was now much easier and cheaper for businesses and individuals wishing to fly drones commercially to now do so. With Part 107 in place, drone sales continued to see exceptional growth. Dunn (2017) stated, “Smartphones sales are cooling, tablets are sinking, and PCs are stagnant, but the demand for drones just keeps on growing.”

Summary

From the dawn of time, the human species have sought to understand the Earth in which they live. Many scientists, philosophers, inventors, and engineers theorized and created many concepts and algorithms we still use today. These individuals helped shape the world and how we view it. The technological achievements we have and see today can be traced back to many of these early philosophers and engineers. But it was the marriage of two revolutionary concepts that evolved much of the world into what it is today.

The marriage of flight and photography opened the door to an age of aeronautics and imaging technology. Conflict and war around the globe made investing in aeronautics and photography a life and death situation. This unfortunate companionship truly pushed these technologies forward in a rather futuristic way and at an astonishing speed. With the creation of the U-2 project and the SR-71 aircraft, aeronautics leaped forward. Additionally, with the creation of these aircraft, imaging capabilities also took a huge step.

As these aircraft were reaching record setting altitudes, countries like the United States and the Soviet Union (Russia) started to set the bar even higher by investing in space travel and satellite technology. These investments quickly paid off and new technologies were born. The birth of the Global Positioning System (GPS) was one such technology that came about from this space race. GPS technology ushered in yet another revolutionary idea of unmanned aerial vehicles (UAVs).

UAVs quickly became a military asset. Utilizing satellite and radio technology UAVs transformed modern reconnaissance and warfare. Then in 1995, President Clinton declassified aerial imaging and some satellite technology. This declassification allowed the private sector to utilize and invest in such technologies. These declassified technologies, and imaging capabilities, paved the way for new and improved technologies like Wi-Fi, Bluetooth, and smartphones to be created.

These new and improved technologies saw additional applications when merged with UAV technology. By joining GPS and personal smart devices with UAV technology, the modern drone was born.

Drone popularity and adoption exploded. Thousands of drones were being sold and paired to smart devices everywhere. This influx of aerial devices started flooding the National Airspace. This drone boom quickly became a regulatory nightmare. At the time, the FAA only had rules and regulations in place for manned aircraft and their pilots. With safety and national security at stake, the U.S. Congress directed the FAA to create

Section 333 Exemption for unmanned aerial systems (UASs). This exemption filled the void of regulation for some drone users but fell short in practicality for others.

After only four years, Section 333 was absorbed and Part 107 stepped forward as the new source of regulation for all drone users. Part 107 now encompassed not only commercial drone users but hobbyists as well. This was extremely critical because hobbyists are now the main consumers of this technology.

Drones have been incorporated in all types of vocations, like ranching, law enforcement, photography, conservation, architecture, real estate, and agriculture. Drone companies and their counterparts are continually changing and improving the technology that goes into them. This continued development has benefited agriculture in a major way. The future of drone technology is bright and their applications in agriculture will be further discussed in this document.

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CHAPTER 2

THE ELECTROMAGNETIC SPECTRUM AND SPECTRAL SENSORS

Introduction

Much of the success we have seen in cameras and photography in the last century can be traced back to our understanding of how light properties work. Light interacts with the earth's atmosphere, its plants, and its many diverse surfaces. It is this interaction that spectral sensors and cameras try to capture. Being able to capture these interactions has proven valuable in multiple areas of agriculture.

Light & Electromagnetic Radiation

In the early years of photography, people only had a limited understanding of light and the dimensions involved. The most fundamental understanding came from Sir Isaac Newton's work with light in the 1670s. Newton's work stated that light was composed of different colors like red, orange, yellow, green, blue, and violet. Newton proved this by splitting white light into those colors by the use of a prism (Newton, 1671).

Newton's Theory about Light and Colors was really only the tip of the iceberg when considering the properties of light. One particular advancement in photography came when the connection between James Clerk Maxwell's theory of electromagnetic radiation (EMR) from 1865 was more fully understood and combined with Newton's theory about light (Domb, 2019).

To understand how photography and modern cameras work, it’s imperative to have a basic understanding of Maxwell’s theory. Electromagnetic radiation refers to how light emitted from the sun acts more like a wave instead of individual energy particles (Physics University, 2019). The energy of a wavelength, determines how much is absorbed or reflected by our atmosphere, plants, and the earth’s surface.

Electromagnetic radiation occurs across the electromagnetic spectrum. This spectrum is classified by the characteristics of the different frequencies. These wavelengths or frequencies have been more clearly identified in the last century and have been given mathematical values. Today we often specify a particular region of the electromagnetic spectrum by identifying a beginning and ending wavelength (or frequency) and then attaching a description (Jensen, 2007). Sections of the spectrum are referred to as a band, channel, or region (Jensen, 2007). Additionally, names of these wavelength regions have been assigned and are more commonly referred by their wavelength strength: radio, microwave, infrared, visible, ultraviolet, X-ray, and gamma ray (Figure 1).

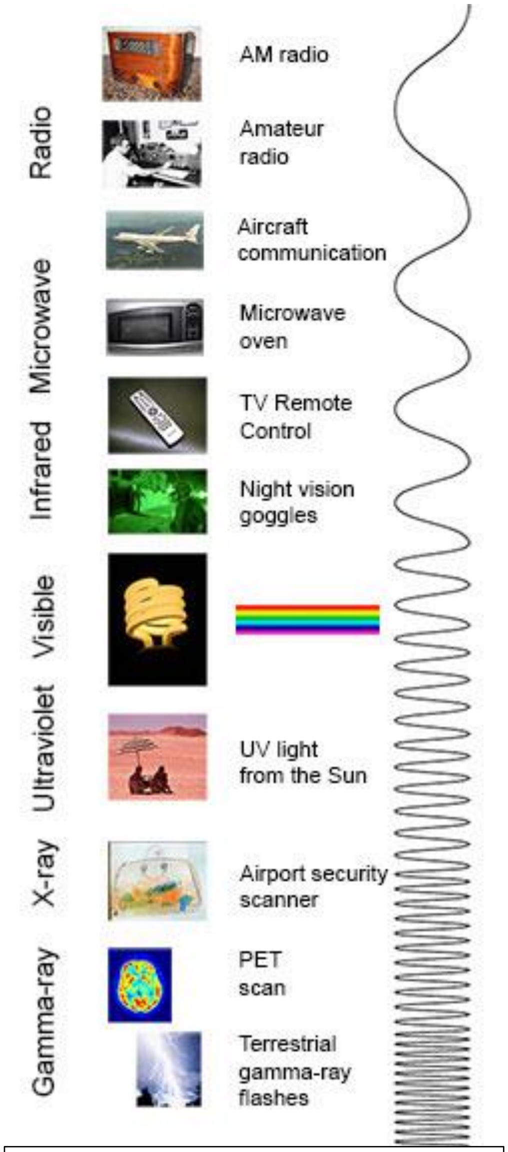


Figure 1. The electromagnetic spectrum from the lowest energy/longest wavelength (at the top to highest energy/shortest wavelength (at the bottom). Credit: NASA Imagine the Universe)

Another important concept to the electromagnetic spectrum is the absorption, scattering, and reflectance of the light wavelengths when they come in contact with the earth's atmosphere and its surroundings. Depending on how much light is absorbed, scattered, or reflected by Earth's elements, determines how certain objects are viewed by the human eye, on film, or as a digital image.

For instance, chlorophyll in vegetation absorbs much of the incident blue and red light for photosynthetic purposes. Most vegetation doesn't absorb the green light, and it is reflected back into the earth's atmosphere (Jensen, 2007). This reaction and combination of absorption and reflectance is what makes most vegetation appear to be green to the human eye. By understanding the basics of the electromagnetic spectrum, a better comprehensive analysis of the types of cameras and sensors used today can be attempted.

Types of Cameras & Sensors

Spectral cameras and sensors are able to view and capture very broad or narrow bands within the electromagnetic spectrum. Combining these spectral sensors with drone technology, a new visual perspective of agriculture can be achieved. In this chapter, examples of different cameras and sensors that have the ability to be attached to a drone will be discussed.

Thermal Sensors

Thermal technology was first developed and used in Britain for anti-aircraft defenses (Monash, 2004). Unfortunately, the development of the images were too slow, and this technology didn't see too much use (Kruse and Skatrud, 1997). Thermal imaging utilizes electromagnetic energy. Any object that has a temperate above absolute zero (0

K), will emit energy that’s detectable in the thermal field (Jensen, 2007). Fortunately, today’s engineers have developed thermal cameras and sensors that are sensitive enough to detect thermal infrared radiation (Jensen, 2007). These thermal cameras and sensors now make it possible to monitor and view what was once invisible to the human eye.

Today there are two main types of thermal imaging devices, cooled and uncooled. An uncooled thermal imaging device is the most common. The infrared detector elements are contained in a unit that operates at room temperature. They are less expensive, but their resolution and image quality tend to be lower than the cooled thermal device. In the cooled thermal imaging device, the sensor elements are contained in a unit which is maintained below 0 °C. They have a very high resolution and can detect a temperature difference as low as 0.1 °C, but they are expensive pieces of equipment (Vadivambal and Jayas, 2001).

Thermal technology for drones also comes with a hefty price tag. A consumer can expect to pay upwards of $3,500 to $10,000 for some of the popular thermal cameras and sensors available for drone use (MicaSense 2019; and FLIR, 2019). With this kind of price tag, many growers and crop consultant may not be able to invest in this type of technology.

With these types of cameras and sensors, significant temperature changes that have taken place in an object, can now be seen over time (Quatrochi and Luvall, 2004). Being able to possibly identify surface damage, disease, insect pressure, and plant transpiration, thermal imaging can become a growers ally.

In agriculture, research operations have looked at stomatal conductance and canopy temperature (Stoll and Jones 2007), plant diseases and pathogens (Stoll et al., 2008), nucleation and freezing behavior of plants (Fuller and Wisniewski, 1998), fruit ripening recognition (Stajnko et al., 2004), seedling viability, estimating soil water status, estimating crop water stress, and scheduling irrigation (Vadivambal and Jayas, 2001). Thermal imaging cameras have great potential in agriculture, depending on the data needed or needs.

Thermal imaging is excellent at assessing plant temperature, which is correlated with plant’s water status (Jones et al., 2002). Furthermore, thermal imaging has also allowed better monitoring of stomatal conductance. Stomatal conductance can be a better indicator of plant response to drying soil than monitoring water potential because reductions in stomatal conductance can occur even before changes in plant water status (Jones, 2004). Being able to determine changes in a plant’s transpiration rate is valuable information. Pathogens like leaf spot and rust can induce well-defined changes, and soil pathogens like *Rhizoctonia solani* or *Pythium* spp. often influences the transpiration rate and the water flow of the entire plant (Mahlein, 2015).

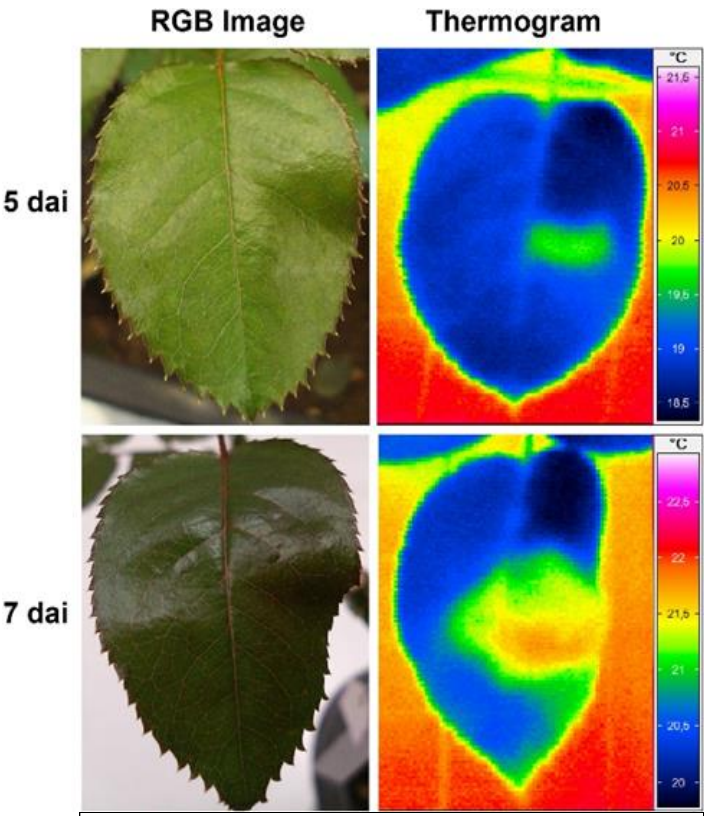


Figure 2.
Monitoring of rose leaf colonization by *Peronospora sparsa* and symptom development of Downey mildew in early stages (5 and 7 days after inoculation) of the disease by thermographic imaging (Modified From: S. Caro, 2014, p.73)

An issue with many foliar pathogens is that by the time it's detected, the pathogen has already inoculated other nearby plant tissue or has completed its life cycle. This becomes problematic for any disease management plan. With the use of thermal imaging a grower could potentially catch a pathogen early enough to treat, remove, or isolate the infected plant. Caro (2014) attempted just that by monitoring the infection and spread of downy mildew (*Peronospora sparsa*) on different *Rosa* cultivars using thermal imaging (Figure 2). The thermal sensors were able to detect the inoculation sites as early as 3 days after inoculation. Warm areas at the inoculation site were followed by a decrease in the leaf temperature of the inoculated leaflet. The temperature of neighboring leaflets then declined as the infection progressed. During much of this time, no changes in leaf tissue or presence of structures of the pathogen on the leaf surface of the three cultivars were detected visually (Caro, 2014). With day to day drone flights and in-depth spectral imaging, the potential to maximize yield and to safeguard crops against further pathogenic infection increases.

Multispectral Sensors

Multispectral cameras and sensors have the capability to capture near-infrared radiation and ultraviolet light at the same time. Multispectral cameras capture certain regions of radiation that are completely invisible to the human eye. The unique capabilities of using multispectral imaging were first fully recognized in the 1960s.

A professor in the Forestry Department at the University of California, Berkley started formulating the multispectral concept and its interpretations (Colwell, 1997). Professor Robert Colwell documented that in agriculture and forestry environments, multispectral measurements with discrete wavelength regions (bands) were usually more valuable than acquiring single broadband panchromatic-type imagery (Jensen, 2007).

Currently, multispectral imagery is collected in a digital format. The digital format is a collection of the light measurement values of three to fifteen spectral bands, depending on the type of sensor (Hagen and Kudenov, 2013). Multispectral cameras have been integrated into systems in order to acquire useful images that can be used for crop classification and mapping, crop forecasting and yield predictions, crop status and condition, weed detection, disease detection and nutrient deficiency, and photosynthetic pigment content (Berni et al., 2009).

The most prominent use of multispectral cameras and sensors on drones and satellites has been in developing Normalized Difference Vegetation Index (NDVI) maps. NVDI measures crop stress and is a good indicator of crop health (Paredes et al., 2011).

NDVI uses light reflection in the red and near infrared bands to discriminate vegetation from soil and find stressed vegetation or infected crop areas (Paredes et al., 2011).

Another type of measurement that is starting to be utilized more in agriculture is the Normalized Difference Red Edge Index (NDRE). NDRE uses multispectral banding from slightly different areas than NDVI. Much like NDVI, NDRE has a similar formula, but this formula uses the RedEdge band instead of the Red band. As plants mature, NDVI can plateau and may be less useful for measuring vegetation health. NDRE can be a more valuable index when collecting data and monitoring stress or health over mature plants (MicaSense, 2019). Additionally, NDVI and NDRE research has been done to see the potential a drone could have when trying to sense a crop’s Nitrogen Use Efficiency (NUE). This research has found that drone based active multispectral canopy sensors can serve as a promising sensing solution for the estimation of a crop’s nitrogen (N) status (Li et al., 2018).

Nitrogen is an essential nutrient in many cropping systems due to its vital role in improving plant health and productivity. According to the Food and Agriculture Organization of the United Nations (FAO) an estimated 200 million tons of nitrogen fertilizers were used in 2018 and is expected to increase by 1.8% a year (FAO, 2018). However, over-application of N fertilizers is the alarming issue that has caused low N use efficiency, leading to N deposition and water eutrophication (Li et al., 2018). Drone-based active sensing is expected to offer flexibility, affordability, and applicability for large-scale monitoring to improve the nitrogen use efficiency of a farming operation (Li et al., 2018).

A study using a drone-based multispectral sensor was conducted to improve the nitrogen use efficiency in five locations in Chinese rice and wheat fields. The research showed that proper calibration of the sensor was critical in obtaining correct values. Once this was achieved, the data acquired could generate proper NDVI and NDRE models. These models then proved successful and drone-based sensing was validated as a valuable way to monitor and correct nitrogen use (Li et al., 2018).

This study is one of many examples that demonstrated the improvements that drone technology and multispectral analysis has seen in last decade. As more research is conducted, additional applications and uses for drone and multispectral sensors will be recognized.

Hyperspectral Sensors

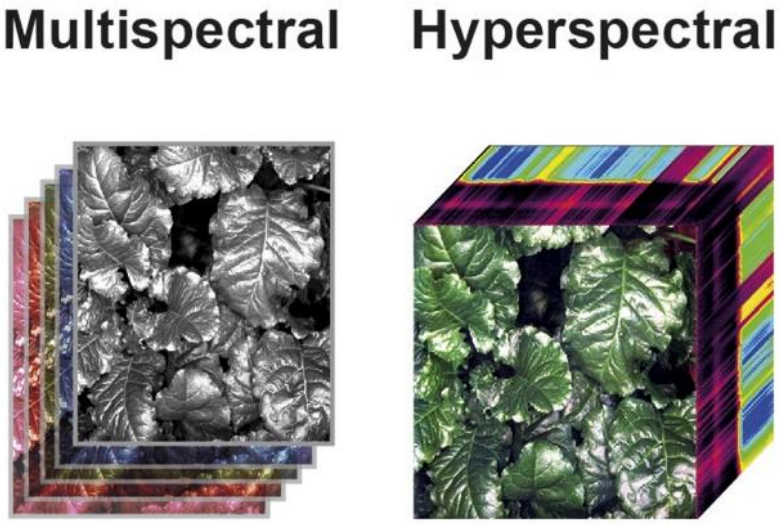


Figure 3.
Difference between Multispectral (Left) and Hyperspectral imaging (right)
Image from: Oerke et al, 2014 (modified image)

One of the issues with hyperspectral information is how often the term hyperspectral and multispectral becomes interchangeable. The field of spectral imaging is plagued with inconsistent use of terminology (Hagen and Kudenov, 2013). This misunderstanding typically can be boiled down to a definition error. It is not the number of measured wavelengths that defines a sensor as hyperspectral, rather it is the narrowness and contiguous nature of the measurements (Miglani, 2010). Multispectral imaging deals with several images at “discrete and narrow bands”, from the visible to the infrared wavelength, whereas hyperspectral sensing deals with imaging in narrow spectral bands over a contiguous spectral range, and produces the spectra of all the pixels in the scene (Figure 3) (Miglani, 2010).

The benefit of hyperspectral imaging is that it provides greater detail of the Earth’s surface than a multispectral image would (Miglani, 2010).While this imaging capability can be extremely valuable, it comes at a cost. Some of the most popular hyperspectral sensors cost more than $35,000 (Blue Skies Drone Shop, 2019). Analysis of hyperspectral data often requires the use of very powerful and sophisticated cleaning software. Software packages like ENVI can be calibrated to clean up the raw hyperspectral data. ENVI software removes issues caused by atmospheric interference, topographic effects, and sensor errors (Jensen, 2007).

With the use of multi and hyperspectral cameras, detection of plant pathogens like rust, powdery mildew, and leaf spot have been caught in their early developmental stages (Rumpf et al., 2010). Additionally, multi and hyperspectral imaging has proven to be useful for monitoring head blight (*Fusarium graminearum*) in wheat and barley (Bauriegel et al., 2011), apple scab (*Venturia inaequalis*) in apple (Delalieux et al., 2007), or late blight (*Phytophthora infestans*) in tomato (Wang et al., 2008). Furthermore, Bravo et al. (2003) used hyperspectral images for the early detection of yellow rust infected wheat.

Hyperspectral imaging has been used to detect mycotoxins in many small grain crops. Mycotoxins are secondary metabolites produced by microfungi that are capable of causing disease and death in humans and other animals (Bennett and Klich, 2003). Early detection of mycotoxins is extremely important not only for the grower, but the consumer of the product as well, so early detection of the infection would be extremely valuable.

Fusarium ssp. produces mycotoxins and infects many crops like wheat, oats, barley and rye. The use of hyperspectral sensors were used to detect head blight (*Fusarium ssp.*) in wheat. Bauriegel et al (2011) discovered that *Fusarium* infestation can be detectable, but it has its challenges as well. The detection of *Fusarium* was possible and could easily be recognized by hyperspectral analysis during BBCH-stage 71–85. Separation of healthy and diseased tissues was most effective in BBCH-stage 75, and a 91% correct classification of *Fusarium* was achieved in the collected samples (Bauriegel et al, 2011). However, *Fusarium* could not be detected by spectral analysis immediately after infection, due to missing symptoms. Additionally, this research found that separation of diseased and healthy tissues is also impossible if ears are fully ripe, and chlorophyll is decomposed, even in healthy tissues.

By using multi and hyperspectral imaging a grower has the potential to transform their management strategy in accordance to the imagery data acquired. Seeing plant physiological changes through these cameras and sensors, allows a grower the ability to act instead of react to plant health issues within the field. Mapping the heterogeneity across a given farm has given many growers a more in-depth knowledge of what’s happening in their fields. Additionally, this knowledge has led to independent field applications of variable rate herbicides, pesticides, fertilizers, and irrigation (Tenkorang and Lowenberg-DeBoer, 2004).

Many herbicides, pesticides and fertilizers are used to improve the overall crop yield. Excessive use of these materials should be avoided to minimize environmental impacts. Hyperspectral imagery is helping to reduce the amount of products being used in the environment (OSU, 2003). Cilia et al (2014) used airborne hyperspectral imagery to develop variable rate nitrogen fertilizer maps. Multiple corn fields were analyzed using hyperspectral sensors in hopes to reduce or to better utilize the nitrogen fertilizer. The study proved that airborne hyperspectral imagery can be used to detect N deficient areas in corn crops (Cilia et al, 2014).

LiDAR

Agricultural land comes in all shapes and sizes and is topographically diverse. Being able to accurately map these agricultural fields is a challenge. As technological advancements have improved, our abilities to more accurately create and map different ecological regions of agriculture has also improved. With the development of Light Detection and Ranging (LiDAR), the ability to map and digitize topographic changes became possible. LiDAR technology can be used to provide elevation data that is accurate, timely, and increasingly affordable in hospitable or inhospitable terrain (McGlone, 2004). Additionally, LiDAR offers an

LiDAR

$$D = \frac{r * t}{2}$$

Figure 4.
D = Distance from the sensor to the target
r = rate of speed (speed of light = $3x10^8$ m/s)
t = time is takes for laser to return
Note: time is divided by 2 because the laser light must travel to the object and

alternative to *in situ* field surveying and photometric mapping techniques for the collection of elevation data (Maune and Nayegandhi, 2007).

LiDAR imaging is unique when compared to other spectral sensors. What makes LiDAR so fascinating and unique is how the data is acquired. LiDAR uses its own light source to generate the elevation data and the way this works is fairly simple. LiDAR sensors calculate the distance (D) light travels by taking the speed of light (r) and multiplying it by the time (t) it takes to detect the light returning back to the sensor (Figure 4). The use of this simple mathematical formula produces remarkable elevation topographic images that are very useful in agriculture.

This technology has one major advantage over other sensors, in that data can be acquired day and night. Without the invention of the laser, LiDAR wouldn't be in existence today. The world was introduced to LiDAR technology in 1971 when Apollo 15 mapped the topography of the moon's surface (Sun, 2012).

Up until about 2016 most LiDAR sensors needed aircraft to carry them (LeddarTech, 2016). The sensors were too big and heavy for small remote controlled aircraft. The drone LiDAR sector is growing rapidly, especially over the past few years. In only a short period of time, manufacturers of LiDAR sensors have engineered LiDAR sensors for small drones (Corrigan, 2019). The output from these drone LiDAR sensors is outstanding and will keep improving as more manufacturers enter this sector. Over the coming years, LiDAR sensor work will move from aircraft to drones (Corrigan, 2019).

At the moment, applications for LiDAR use in agriculture is minimal and still cost a significant amount of money. The most promising areas of agriculture that LiDAR imaging is impacting is soil monitoring and erosion detection. Soil erosion is a significant issue and topic in agriculture (Foss and Moran, 1984). With the help of drone technology and LiDAR, monitoring soil erosion is simplified. Soil erosion is still a significant problem in the Midwest. Some states like North Dakota and Minnesota estimate that as much as 19 inches of topsoil has been eroded from agricultural fields (DeJong-Hughes et al., 2011). Yearly soil monitoring using LiDAR on drones could potentially help in creating a better soil management plan by mapping the change in elevation of a field. This kind of strategy and technology could help reduce erosion and help sustain a valuable resource.

Red, Green, Blue (RGB) Sensors

Today, many drones come with a standard camera that captures the red, green, and blue (RGB) regions of the electromagnetic spectrum. These types of cameras are very common with drones because the images they produce recreate almost exactly what our eyes see (Herrick, 2017). In agriculture, RGB cameras have seen significant use. With an RGB camera on your drone, you can see an entire field all at once. With this capability, a grower can process the aerial images in real time. This allows the grower to quickly make observations and locate the problem area (Herrick, 2017). Furthermore, RGB imagery can also be used to create orthomosaic maps. Orthomosaic maps are a grouping of many overlapping images of a defined area which are processed to create a new, larger scaled map (newstorymedia, 2019). This type of map can then be used for georeferencing and data input because it's true to scale.

Another option growers have by using a RGB camera is the Visible Atmospherically Resistant Index (VARI). VARI is used to detect areas of crop stress. The VARI algorithm (Figure 5) uses some color correction to minimize reflectance, scattering, and other atmospheric effects to better estimate the fraction of healthy vegetation in an area (Herrick, 2017). Effectively, it exaggerates color and shows how green the plant is in comparison to others so you can approximate plant health and vigor (Herrick, 2017). VARI is not to be confused as a replacement for Normalized Difference Vegetation Index (NDVI). The biggest asset of using VARI is that it's compatible with RGB cameras and if that's the only camera at your disposal, it's a nice option to have.

$$\mathit{VARI} = \frac{\text{Green} - \text{Red}}{\text{Green} + \text{Red} - \text{Blue}}$$

Figure 5.
VARI index compares and adjusts the red, green, and blue bands of light to display an approximation of overall crop health.

Currently, most RGB cameras are being used outside of agriculture. Being able to fly and capture images and videos from an entirely new vantage point, RGB cameras have helped drone adoption around the world. Many RGB cameras have been engineered to capture very high quality digital images and video. This capability has become very popular amongst drone hobbyists and outdoor enthusiasts.

Introduction to Precision Agriculture

In the last 30 years, technological advancements in farming equipment as well as aerial imagery has brought forward a new kind of “smart farming”. Smart Farming represents the application of modern Information and Communication Technologies (ICT) into agriculture, leading to what can be called a Third Green Revolution (Smart-AKIS, 2016). Growers in the twenty-first century have access to the internet, Wi-Fi, GPS, digital field mapping, soil scanning, satellite imagery, data management, and drone technology. By precisely measuring variations within a field and adapting the strategy accordingly, growers can greatly increase the efficiency of pesticides, herbicides, and fertilizers, and use them more selectively (Schuttelaar and Partners, 2017).

Smart farming has also been called precision agriculture by many growers and industrial companies. Precision agriculture is quickly evolving and becoming of high interest to many growers and agricultural businesses. Increased interest has led to more investment in camera and drone technology. Through research and development many of the camera and sensor developers are trying to understand the full benefits they can provide on an agricultural platform.

Precision agriculture has major promise in generating additional efficiency for many growers. One issue slowing the adoption of precision agriculture is that many technologies that have been rolled out are well in advance of the farmer’s ability to create value from them (Schrimpf, 2016). Even if a grower sees the value of such technology, the ability to invest in drone and spectral sensing equipment may be unrealistic financially. Drone technology and variable rate mapping and planting is a prime example.

Drones have proven that they’re an excellent piece of technology and a great platform for precision cameras and sensors. Even with this knowledge, growers are not going to invest in this new technology right away. Furthermore, drones are exciting pieces of equipment, but they're a bit daunting to the average person or grower. Many first time drone buyers face what has been called "drone anxiety". This anxiety is extremely common, and for a good reason. Drones are expensive and no one wants to crash a costly piece of equipment they spent a good amount of money on. Additionally, many people experience fear and anxiety when using a new kind of technology (Drone Supremacy, 2016). Agricultural drones typically encompass both, a new technology and a costly investment.

Most growers are already limited on time and have a strict budget. With the only prescription for drone anxiety being time, patience, and practice, the probability of grower seeking out a new piece of technology that requires time and patience isn't likely. Growers simply don't want to spend more money and time learning how to use a new piece of technology. This is one problem has dramatically slowed the adoption and investment of drone and precision technology in agriculture.

The earliest adopters of precision agricultural and drone technology have been those that have weighed out the benefits of incorporating precision tools in their management plan. To get the most out of owning a drone, one must first take the time to identify what the primary uses will be for the drone. By determining the primary and secondary goals of the drone, one can then research and eventually purchase a drone that will best fit their needs (Cler, 2017). A study conducted by Successful Farming released the following statistics from their 2016 Technology in Ag Study:

- 9% of the Ag industry already owns a drone
- An additional 3% of the Ag industry will own a drone within the next 12 months

- 17% of the Ag industry will own a drone within the next one-to-two years
- 33% of the Ag industry will own a drone within two or more years
- 38% of the Ag industry doesn’t plan to purchase a drone (CHS, 2017)

The statistics listed above clearly lays out the small percentage of early adopters and those that still need to weigh out the options of investing in drone technology. For those early adopters, management strategies are already evolving as a result of investing in drone technology and precision agriculture.

Growers that have incorporated precision technology into their agronomic management plan are receiving a financial return as well. Many growers in Brazil, facing weed control issues, have used precision technology to modify their herbicide applications. Multispectral sensors and precision technology has brought many Brazilian growers savings, varying from 20% to 90% and is directly proportional to the level of weed infestation, the precision technology being used, and acreage (Trevisan, 2017). Land size plays a key role into investing in precision agriculture. It has been found that late and non-adopters to precision agriculture consist entirely of farms of less than 2,000 acres (Hopkins, 2019).

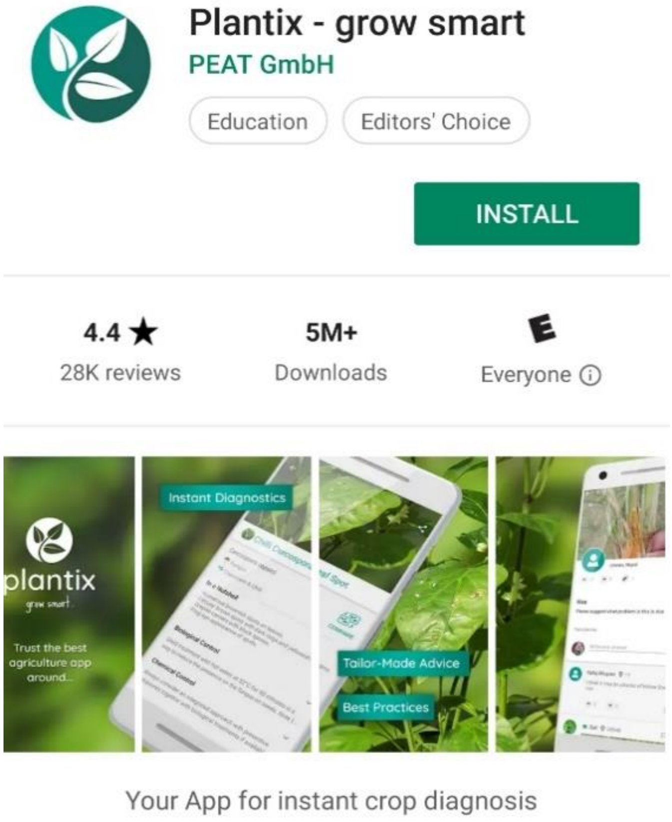
Precision agriculture has proven its worth to many growers in Alberta, Canada. The University of Lethbridge showed that 81% of irrigators have adopted some form of spectral imaging or precision agriculture, at an average of five technologies per irrigator. The crops being grown is this survey ranged from wheat, rye, barley, canola, rapeseed, and alfalfa. The survey showed that, under precision agriculture, crop yields have increased an average 20% and yearly crop quality has increased by an average of 16%. Yearly reductions in irrigation water, fertilizer, herbicides and pesticides have ranged between 14% and 24% (Hopkins, 2019).

Precision agriculture and drone technology have a bright future. Every year, new adopters in the private and industrial sectors of agriculture invest in precision technology. With the current view and understanding of how much agriculture impacts the environment, precision agriculture and its encompassing technologies will quickly become the way of future.

Precision Gardening

Currently, digital cameras and sensors which feature RGB capabilities are bolstering the value of precision agriculture for the public as well. Smart phone technology and digital imaging capabilities has taken an outstanding step forward in the last five years. This achievement has led many urban farmers and gardeners towards precision imaging through the use of their smart handheld devises (Frail, 2010).

Many people today are passionate about gardening and growing plants in an urban setting (Frail, 2010). Often, many individuals have limited knowledge about growing plants and the problems that can happen during the growing season. The age of technology now allows people to receive instant



Your App for instant crop diagnosis

Figure 6. Plantix App for Android and iPhone smart devices
Source: C. R. Wynn (Samsung Galaxy S9)

information about whatever they want. This now includes gardening tips, seeding rates, plant disease recognition, insect identification, and plant identification. Much of this information is a result of using a RGB camera on the user's smart device. For example, if the individual notices spots on their plants, and are worried that they have a disease, they can take a picture of the damage through the provided gardening app. Plant experts will then review the photo and get back to the gardener on what is wrong with their plants (Garden Compass, 2015). Many are benefiting from downloading the available information so they can begin their gardening journey (Flowers, 2016).

Digital RGB image analysis is a well-established technology, currently it is now being used for plant disease assessment. Several software packages for both iPhone and Android devices are coming to, or are already, on the market. Phone apps like Leaf Doctor, BioLeaf, Garden Compass, PlantSnap, and Plantix (Figure 6) use the RGB camera on the user's smart device to identify plants and pathogens. This developing technology uses the color distribution to analyze plant disease. The parameters for healthy and diseased areas can be adjusted by the user in a well-organized, graphical user interface (Mahlein, 2015). These apps can lead the user to develop and map out areas that need additional attention and treatment (Flowers, 2016). These smart device apps provide a basic approach to precision agriculture for individuals with little to no botanical or agricultural experience.

Conclusion

Traditional agriculture management practices assume that parameters in crop fields are homogenous, thereby resulting in an all-encompassing application and plant management strategy (Hillnhütter and Mahlein, 2008). Whereas precision agriculture aims at examining spatial heterogeneities within crop stands (Mahlein, 2015). Drone technology can be a tool to help growers evolve from a homogenous management strategy and move towards a more heterogeneous approach within their fields. Unfortunately, due to the cost of many spectral sensors, a homogeneous approach will be more common for growers and crop consultants until prices drop significantly.

The sensors a drone can carry have the ability to assess the optical properties of plants within different regions of the electromagnetic spectrum and can utilize information beyond the visible range (Mahlein, 2015). The cameras and sensors have the ability to detect the early changes in plant physiology due to biotic stresses. Plant stressors can affect many physiological elements of a plant. For instance, plant diseases and nutritional deficiencies can cause modifications in tissue color (chlorophyll), leaf shape, transpiration rate, canopy morphology, and plant density. These changes will impact the variation in the interaction of solar radiation with plants (West et al., 2010).

Drones in agriculture have produced some fascinating results that growers can truly benefit from. Recent research has shown many benefits of using multispectral, hyperspectral, thermal, and RGB sensors in agriculture. While these benefits have shown promise on the agricultural platform, many growers are yet to adopt these new pieces of technology. Drone technology isn’t cheap and poses its own set of difficulties.

The early adopters that have overcome the learning curve of precision technology have seen the benefits of their investment and many are seeing forms of financial return. Often, this financial return comes in the form of a diversified management plan instead of an all-encompassing homogeneous approach for every field. This diversified approach has helped growers use herbicides, pesticides, and irrigation more efficiently, and it’s this efficiency that’s added financial return.

An additional hurdle spectral cameras and sensors face is the amount of image data they produce. Five years ago, this was a fairly common concern because many computers weren’t capable of processing that amount of data. Today, this hurdle is quickly being overcome as technology and computing capabilities improve greatly every year.

A correlation between late and no-adopters of drone and precision technology can be potentially explained by the amount of acres that a grower has in production (Figure 7). With the average farm size being 251 acres in the United States (MacDonald and Hoppe, 2017), investing in new farming technology may not produce any beneficial return. This is a crucial consideration for the adoption of drone technology and precision agriculture.

Small family farms accounted for 90 percent of all U.S. farms and 24 percent of production in 2015

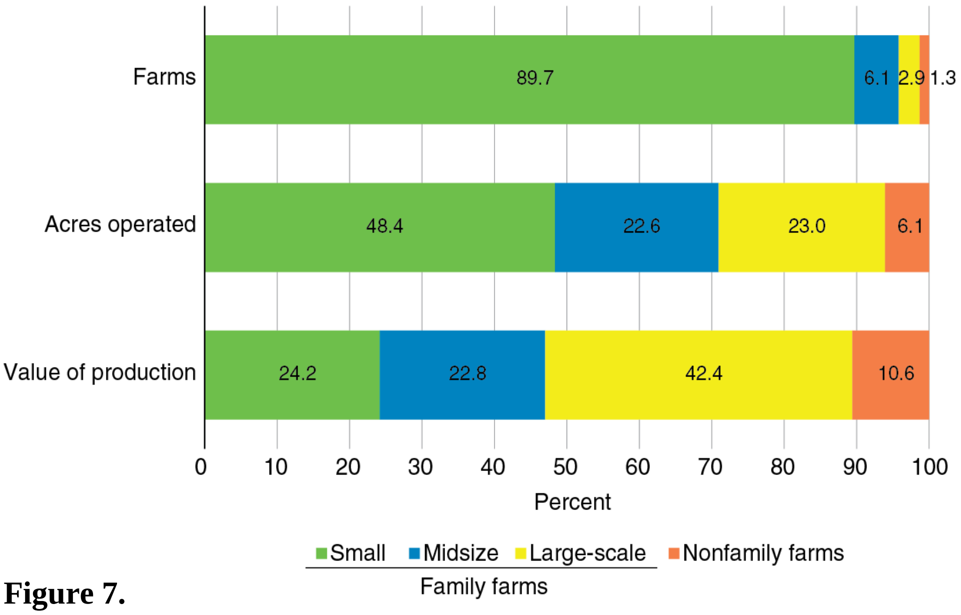


Figure 7.

Note: Farms are categorized by their annual gross cash farm income (GCFI): under $350,000 (small), between $350,000 and $999,999 (midsize), and at least $1 million (large-scale). Nonfamily farms are those where neither the principal operator nor individuals related to the operator own a majority of the business.
Source: USDA, Economic Research Service and National Agricultural Statistics Service, 2015 Agricultural Resource Management Survey.

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CHAPTER 3

AN AGRICULTURAL CASE STUDY & INVESTING IN DRONE TECHNOLGY

Introduction

Agriculture has seen significant changes in the last 60 years. Farm equipment now has yield and moisture monitors, twin rotor systems that allow the cutting and separating of the crop in one pass, and GPS systems that auto steer the equipment throughout the field. Farm equipment today is advanced technology. One technological advancement that has taken the agricultural industry by storm is precision field mapping. In the last twenty years, spectral imaging from airplanes and satellites has benefited growers with an additional management tool. Today, drones and spectral sensors are available for growers to improve their farm management strategies.

With any new investment, a grower must evaluate the costs and potential returns to determine its economic feasibility. Before investing in a new piece of equipment or technology, a grower needs to identify the problem and whether the new equipment will be an economic solution. This chapter will address issues and concerns that many growers and agricultural businesses have when considering the investment of drone and precision technology. A case study of a spring wheat infested with wild oats (*Avena fatua*) in Jamestown, North Dakota will be looked at.

Introduction to the Case Study

The case study that will be discussed is one of many examples where drone technology could be a possible solution, and an additional tool, a grower or crop consultant could use when facing crop management decisions. A drone based precision map was the desired outcome for this case study. This map would have helped to magnify the potential management strategies needed to gain control of a noxious weed infestation.

Many questions and facts regarding drone technology needs to be addressed prior to any investment decision. Before any drone purchases are made, the goals for the drone should be listed. This list needs to contain the benefits and drawbacks of purchasing a drone for commercial agricultural use. For many growers and commercial agriculture businesses, the process of acquiring a drone for aerial imaging and spectral sensing goes as follows.

Typically, the first question agricultural drone consumers ask is: “What can be seen using a drone?” Often, this discussion only includes imaging analysis provided by a RGB camera. While this is still a good option, it leaves out the most beneficial sensors available for agricultural use. This happens because the grower or business isn’t aware of the other spectral sensors available for drones or they don’t want to spend the money investing in expensive spectral cameras. Furthermore, even if the consumer is aware of the sensors available, and they wanted to invest, many individuals stumble on how these sensors are used for precision imaging and field mapping.

Precision mapping of a field is the product often desired by many growers, consultants, and business, but very few know how to capture the spectral imagery and process the data. This hurdle is one of the main reasons that drone technology in agriculture hasn’t progressed forward at a more rapid rate. For those individuals willing to research and seek out the technology and software necessary for processing the drone aerial data, they often get lost in the terminology that’s used by many spectral software companies. This lack of understanding often leads to an abandonment in pursuing drone and precision technology.

If the grower or agricultural business is able to overcome these early hurdles of adoption, they’ll move to the next major question: “Is this drone investment economically feasible and what kind of return can I expect to see?” The answer to this question will vary greatly depending on the application the grower or business wishes to use the drone and the spectral sensors. Answering this question truthfully leads many towards acquiring or walking away from this management tool.

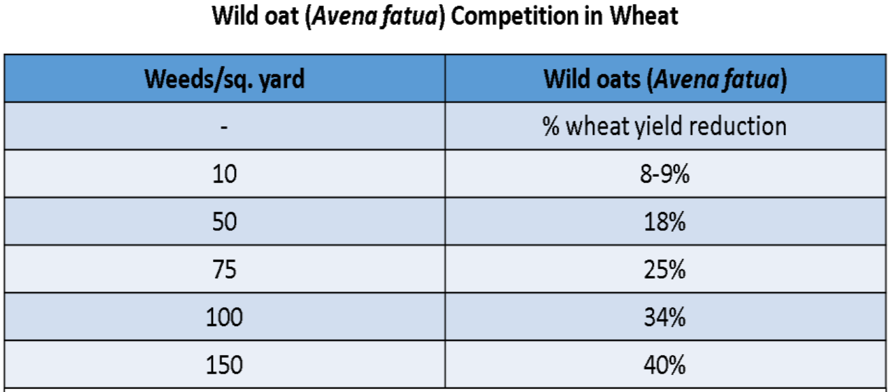
If the economic feasibility and net return of the investment is justified, the growers, crop consultants, and business have one final obstacle to navigate, the purchase. Purchasing a drone and sensors isn’t an easy task. As discussed in earlier chapters, different drone sizes and designs are available. The consumer now has to navigate what drone is best for their desired task. Often, many consumers have little to no experience in knowing what drone design is best for their application, so this process is often done through an online search engine and the results are often misleading.

Once a drone design is determined, it is important to find the proper sensor and software. This process can be daunting for first time consumers. As stated earlier, the management application desired determines the kind of sensor that’s needed. All multi and hyperspectral sensors work in a similar fashion; however, they don’t capture the same bands or reflectance values. Typically, a multispectral or hyperspectral camera will come with its electromagnetic spectral bands calibrated and the manufacturer will provide guidance on what bands are being acquired along with calibration guidelines. Sometimes, theses sensors have the capability to calibrate on the fly and produce corrected images. Unfortunately, it is currently impossible to produce precisely equivalent images from two different spectral sensor models, no matter how much calibration is applied (Akopyan, 2016).

Not knowing what spectral bands are best for a particular agricultural application is problematic. Even by knowing what spectral bands are necessary, tension and anxiety can still be an issue when trying to pick the right sensor manufacturer and software package. This final process, if done correctly, takes a lot of time and communication with professionals from within the industry. This too can be problematic because time is something that many growers and business don't have to spare.

Importance of the Case Study

Wild oat (*Avena fatua*) is considered a noxious weed and it infests 28 million acres in the United States every year. North Dakota has the highest rate of infestation, with annual losses ranging from $150 to $200 million annually (Warrick and Baughman, 2019). A strong wheat industry is very important economically to North Dakota because wheat is North Dakota's chief agricultural commodity. Nationally, North Dakota ranks second to Kansas in total wheat production, though there are years when the state has come out on top (NDWC, 2018). North Dakota is number one in the production of two wheat classes: hard red and durum. On average, the state's farmers grow nearly half of the nation's hard red spring wheat (250 million bushels) and two-thirds of the durum



Wild oat (*Avena fatua*) Competition in Wheat

Weeds/sq. yard	Wild oats (*Avena fatua*)
-	% wheat yield reduction
10	8-9%
50	18%
75	25%
100	34%
150	40%

Figure 1: Yield reduction in Wheat from the presence of Wild oats
Numbers Provided By: North Dakota State University, 2019

(50 million bushels). Wild oat is extremely competitive for valuable resources like water and soil nutrients, and directly impacts wheat yield (Figure 1).

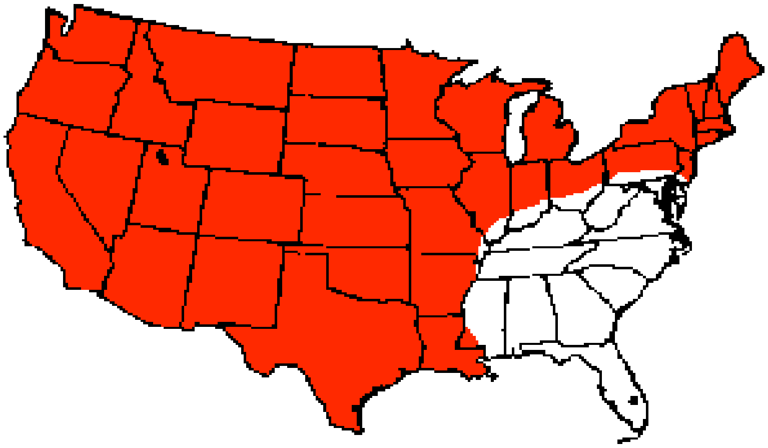


Figure 2.
Distribution of wild oat in the United States (red areas).
Figure From: Warrick and Baughman, Texas A&M AgriLife Extension Service

Wild oat has been an issue in North America for well over 40 years. The species occurs in all Canadian provinces and most states in the USA (Figure 2). In Canada, it is most troublesome as a weed in the prairies, where it has spread throughout crop areas in all climatic zones (Beckie et al., 2012). The sustained presence of wild oats has brought on many management strategies over the past four decades. Cultural and chemical control practices have helped control wild oats in grain fields for many years. Although with repeated use of the same herbicide, a genetic selection of herbicide-resistant wild oats was created.

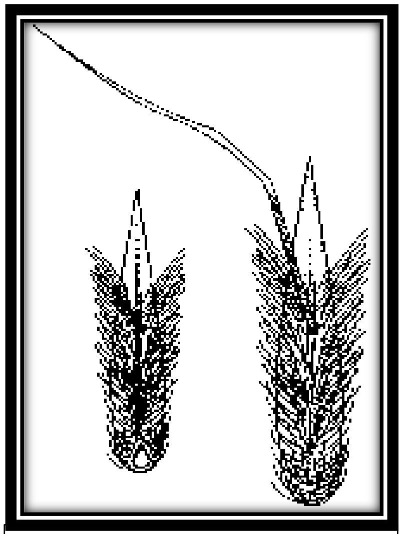


Figure 3.
Wild oat seed, showing "sucker mouth," hairs, and awn.
Figure From: Warrick and Baughman, Texas A&M AgriLife Extension ServiceExtension Service

What makes wild oats so difficult to control and eradicate is the shattering of the seeds before the crops are harvested (NDSU, 2019). Once the wild oat seed shatters, it lays dormant until proper moisture is received. Wild oat seeds possess a unique capability to move and twist the floret awn (Figure 3) when exposed to moisture (Raju et al., 1985). This twisting movement allows the seed to move on the soil surface to locate a suitable impression in the ground. Once the seed falls into a soil impression, the awn florets continues twisting, embedding it below the soils surface. Additionally, wild oat is a cool season plant and seeds germinate in the spring and fall when favorable temperature and moisture conditions exist (NDSU, 2019). These characteristics make it extremely difficult to control and eradicate.

Currently, wild oat is showing resistance to two herbicide family groups, group 1 and group 2 (Gowan, 2016). Group 1 herbicides are called Acetyl CoA Carboxylase (ACCase) inhibitors. Group 1 herbicides work when the plant absorbs the herbicide through the foliage and translocates the herbicide in the phloem to the growing point, where it inhibits meristematic activity (UC, 2019 a). ACCase herbicides inhibit the enzyme acetyl-CoA carboxylase, which catalyzes the first step in fatty acid synthesis, which is important for membrane synthesis (UC, 2019 a).

Acetolactate Synthase (ALS) or Acetohydroxy Acid Synthase (AHAS) Inhibitors are better known as group 2 herbicides. ALS herbicides are readily absorbed by both roots and foliage and translocated in both the xylem and phloem to the site of action at the growing points (UC, 2019 b). ALS herbicides are very diverse in chemical structure and make up, but they all inhibit branched-chains of amino acids which is key for biosynthesis (UC, 2019 b).

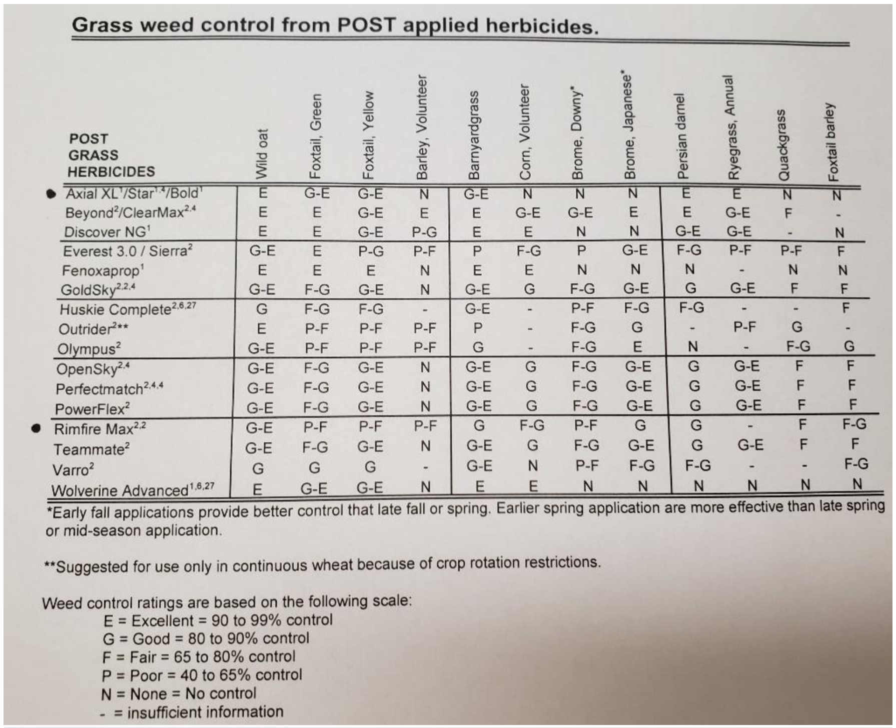
Wild oats resistant to group 1 and 2 herbicides are increasing rapidly. Results from a study conducted in Canada shows a dramatic increase in the number of fields with wild oat herbicide resistance to Group 1 and Group 2 (Gowan, 2016). Additionally, a survey conducted in 2016 showed that groups 1 and 2 were used to target wild oats on

74% of wheat acres, 61% of barley acres, 100% of pea acres, and 42% of canola acres (Stratus Ag Research, 2016). These percentages are staggering and result in strong selection pressure for the further development of resistance.

With herbicide resistance on the rise, a grower's ability to combat wild oats in a wheat field becomes increasingly problematic. Group 1 and 2 resistance leaves many growers with only four possible solutions to manage wild oats in a wheat field:

- Use group 1 and 2 herbicides at the same time with hopes that dual resistance isn't present in their field
- Use herbicides in groups other than 1 & 2
- Rotate to non-grass crops for 3-5 years
- Stop growing wheat and barley indefinitely

Currently, less than 25% of wheat fields have herbicide resistance to both group 1 and group 2 herbicides (Cowan, 2016). Spraying both herbicide groups on a wheat field would increase the chances of weed control, and could reduce the chance of developing herbicide resistances. Unfortunately, this option is unlikely due to



Grass weed control from POST applied herbicides.

POST GRASS HERBICIDES	Wild oat	Foxtail, Green	Foxtail, Yellow	Barley, Volunteer	Barnyardgrass	Corn, Volunteer	Brome, Downy*	Brome, Japanese*	Persian darnel	Ryegrass, Annual	Quackgrass	Foxtail barley
● Axial XL^{1}/Star^{1,4}/Bold^{1}	E	G-E	G-E	N	G-E	N	N	N	E	E	N	N
Beyond^{2}/ClearMax^{2,4}	E	E	G-E	E	E	G-E	G-E	E	E	G-E	F	-
Discover NG^{1}	E	E	G-E	P-G	E	E	N	N	G-E	G-E	-	N
Everest 3.0 / Sierra^{2}	G-E	E	P-G	P-F	P	F-G	P	G-E	F-G	P-F	P-F	F
Fenoxaprop^{1}	E	E	E	N	E	E	N	N	N	-	N	N
GoldSky^{2,2,4}	G-E	F-G	G-E	N	G-E	G	F-G	G-E	G	G-E	F	F
Huskie Complete^{2,6,27}	G	F-G	F-G	-	G-E	-	P-F	F-G	F-G	-	-	F
Outrider^{2**}	E	P-F	P-F	P-F	P	-	F-G	G	-	P-F	G	-
Olympus^{2}	G-E	P-F	P-F	P-F	G	-	F-G	E	N	-	F-G	G
OpenSky^{2,4}	G-E	F-G	G-E	N	G-E	G	F-G	G-E	G	G-E	F	F
Perfectmatch^{2,4,4}	G-E	F-G	G-E	N	G-E	G	F-G	G-E	G	G-E	F	F
PowerFlex^{2}	G-E	F-G	G-E	N	G-E	G	F-G	G-E	G	G-E	F	F
● Rimfire Max^{2,2}	G-E	P-F	P-F	P-F	G	F-G	P-F	G	G	-	F	F-G
Teammate^{2}	G-E	F-G	G-E	N	G-E	G	F-G	G-E	G	G-E	F	F
Varro^{2}	G	G	G	-	G-E	N	P-F	F-G	F-G	-	-	F-G
Wolverine Advanced^{1,6,27}	E	G-E	G-E	N	E	E	N	N	N	N	N	N

*Early fall applications provide better control that late fall or spring. Earlier spring application are more effective than late spring or mid-season application.

**Suggested for use only in continuous wheat because of crop rotation restrictions.

Weed control ratings are based on the following scale:
E = Excellent = 90 to 99% control
G = Good = 80 to 90% control
F = Fair = 65 to 80% control
P = Poor = 40 to 65% control
N = None = No control
- = insufficient information

Figure 4.
Approved Post emergence herbicides in wheat.
Source: NDSU, 2019 North Dakota Weed Control Guide (p. 13)

the rise in resistance and the application costs of applying two herbicides.

According to the 2019 North Dakota Weed Control Guide, herbicides like Axial XL (Group 1) and RimFire Max (Group 2) have a weed control rating of 80%-99%, which is considered to be in the range of "good to excellent" for wild oat control. These two herbicides have the highest post emergence ratings for controlling wild oat (Figure 4). Controlling wild oats with a high rating herbicide also comes at an additional cost. According to the guide, a grower can expect to pay $16.90 an acre for Axial XL and $12.00 an acre for RimFire Max. That's a total of over $28 an acre if both group 1 and group 2 herbicides are applied. That cost still doesn't include fuel and labor costs of the herbicide application. A total cost like that leaves little to no return for the grower.

Using different groups of herbicides for wild oat control in wheat fields has limitations. Herbicides like triallate (group 8), bromoxynil (group 6), and pyrasulfotole (group 27) are possible options. The issue with triallate is that the North Dakota guide suggests applying it before planting and should be incorporated/tilled 3 to 4 inches deep for best wild oat control. This suggestion may be an issue where soil erosion has been a significant problem in the past. By not tilling triallate into the soil, significant loss of the herbicide will be volatilization from moist soil (PubChem, 2018). The guide further states that a delay in wheat planting of 3 days is suggested. Applying triallate before seeding may injure certain wheat varieties (NDSU, 2019). Additionally, one must remember that wild oats lies dormant until conditions are right. This may result in wild oats emerging well after the application of triallate is made.

Bromoxynil is a non-residual, contact herbicide. This means the herbicide requires very thorough coverage to be most effective on wild oat. Furthermore, bromoxynil works best under hot and sunny conditions (NDSU, 2019). These kind of requirements for bromoxynil can also be problematic. As stated earlier, wild oat is a cool season annual and matures well in advance of wheat. The hot and sunny requirement suggested by the NDSU weed guide can become an issue. By the time a real hot and sunny day is available for spraying, wild oat plants may have already taken up valuable nutrients.

Pyrasulfotole is a unique herbicide, in that its family and mode of action is unknown (UC, 2019 c). Pyrasulfotole is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor (site of action), which is new for small grains (EPA, 2007). Pyrasulfotole has seen its most success in weed control when it is combined with bromoxynil. In fact, this combination is so successful that pyrasulfotole is rarely purchased without bromoxynil in the United States. What’s interesting about pyrasulfotole is that it’s only labeled for wild buckwheat, common lambsquarters, redroot pigweed, and volunteer canola when applied by itself (EPA, 2007). When combined with bromoxynil the list of labeled weeds increases and includes wild oat (EPA, 2007). While this combination is a viable option for wild oat control in wheat, it still poses a potential issue. Many of the products that already have the mix of pyrasulfotole and bromoxynil in them also include an additional herbicide from group 1 or group 2. An example of that kind of mix would be Husky Complete and Wolverine Advanced. While both of these herbicide mixes are labeled for wild oat in wheat and have a good to excellent control rating, Husky Complete contains two group 2 herbicides (thiencarbazone & mefenpyr safener), and Wolverine Advanced contains a group 1 herbicide(fenoxaprop) (NDSU, 2019). Combining group 1 and group 2 herbicides in Husky Complete and Wolverine Advanced increases the selection pressure for herbicide resistance.

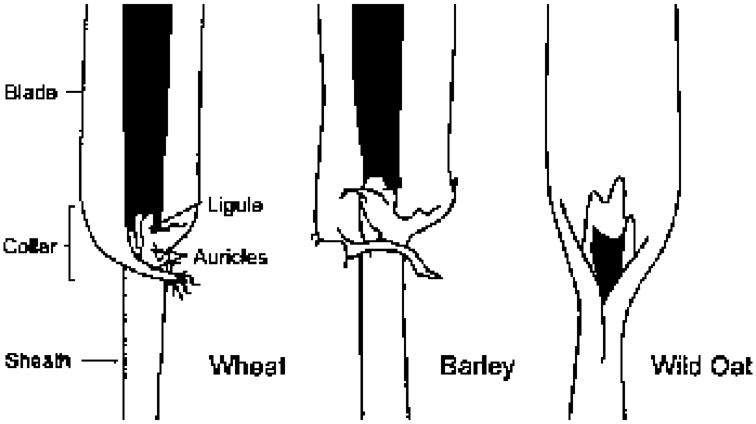


Figure 5.
Wheat, barely, and Wild oat plants (left to right), showing leaf formations
Figure From: Warrick and Baughman, Texas A&M AgriLife Extension Service

One way to increase a grower's chemical and cultural management plan for wild oat is by rotating to a completely different crop family. Wheat, barley, rye, corn, and wild oat are all grasses. Grasses have many identical characteristics (Figure 5) and reacts to herbicides in a very similar way. By rotating away from grasses, more chemical and cultural control options become available. Producing a strong competitive crop is recommended when trying to control wild oats (Warrick and Baughman, 2019). A heavy seeding rate is also recommended, this makes a crop more competitive and may help in areas where wild oats are a problem (Warrick and Baughman, 2019).

Depending on the severity of wild oats in a field, a grower may be faced with never growing wheat or any grass crop again. Due to wild oats dramatic impact on yield and its early maturing date, a grower may be forced to switch to an early season crop to get ahead of the noxious weed. If the problem persists, switching the agricultural land to native habitat or a conservation easement may be needed. Converting land to natural habitat is drastic, but by incorporating native habitat back into the system the perennial cycle is slowly broken over time. Time allows for the breakdown of the seed bank by predation and other biotic factors (Beck, 2013). This option is the most drastic, but with herbicide resistant wild oats increasing every year, growers may have no other option in the next decade.

Case Study

In the summer of 2018, a number of North Dakota wheat growers faced a wild oat infestation throughout a number of their spring wheat fields. This study will focus on one field that was approximately 300 acres of spring wheat. The previous year, 2017, the field was planted to soybeans, and in 2016, the field was planted to spring wheat. In early May, the recommendation was given to use glyphosate (RoundUp) as a pre-emergence burndown for grasses, which included wild oat.

On May15, a wild oat infestation (1-2 leaf stage) was noticed in pockets around the field (Hilderman, 2014). The spring wheat still had not emerged. When emerged wild oats were recognized, a continued recommendation of glyphosate was given to manage the competitive noxious weed.

Approximately a week later, on May 23, the spring wheat had emerged. It was also noted that the grower had not sprayed the field with the recommend glyphosate application, and the wild oats had reached a 2-4 leaf stage. The emerged spring wheat consisted of plants in the 1 to 2 leaf stage. A full rate of Everest 3.0/Sierra (flucarbazone + safener) was recommended for the emerged spring wheat.

The following week, on June 1, the wheat had reached a 2 to 4 leaf stage, and the wild oats were approximately in the 3 to 4 leaf stage. The previous recommendation of Everest 3.0/Sierra was never applied by the grower. Early season moisture and heat accelerated the growth of both the spring wheat and the wild oats. At this time, the herbicide recommendation changed to a full rate of RimFire Max (mesosulfuron + propoxycarbazone + safener) to combat the accelerated growth of the wild oats. This recommendation was not applied until June 8, when the spring wheat had reached a stage of approximately 3 to 5 leaf.

By June 15, affected wild oats were observed throughout the spring wheat field. Control of the wild oats was presumed and no further recommendations were made. On June 21, the presumed control was mistaken and the wild oats were chlorotic and sickly looking, but still growing within the spring wheat. This was surprising because a full rate of RimFire Max had been applied. During this time, the wild oat infestation rate was estimated to be covering approximately 40% of the spring wheat field. A full rate recommendation for Husky Complete (bromoxynil & pyrasulfotole & thiencarbazone & mefenpyr safener) was given to the grower for an immediate application. This application was never applied by the grower.

Due to the nature of the results from the RimFire Max application, a representative of Bayer, the chemical manufacturer was contacted. On June 25, the grower, alongside their crop consultant, met up with the Bayer representative to walk through the field where the wild oats survived the RimFire Max application. During this walk through and conversation, the representative from Bayer agreed with the consultant’s conclusion that herbicide resistant wild oats were likely present in the field.

From this conclusion, a recommendation of rotating out of wheat for 3 to 5 years was given. This recommendation was delivered in hopes of suppressing the wild oat pressure and open up more cultural and chemical control options. Furthermore, other spring wheat fields within a 3 to 5 mile radius experienced similar results as the field discussed in this study. These fields varied in herbicide use, applications dates, and wild oat infestation rates. Wild oat seeds were collected from these fields for further research and verification of herbicide resistance.

Case Study Results

In this case study, the crop consultants discussed purchasing a drone to capture images of the infested wheat field for mapping purposes. They considered the benefits and drawbacks of purchasing a drone. All of the hurdles and obstacles discussed earlier were brought up. The consultants had some understanding of drone technology and its capabilities, but the biggest issue addressed was the economic feasibility.

To invest in drone technology, a financial return needs to be attainable. Being able to precisely map and calculate the infestation rate of the wild oats would have produced a product that could have been sold and marketed to other growers facing a similar management issue. Thus, it was determined that a potential precision map acquired by a drone could have paid for itself within that first season.

Once the economic feasibility was determined, a decision had to be made on an optimum drone platform. Many crop consultants conduct a majority of their work from a pickup truck and travel many miles to see their growers. Due to travel and limited storage space, many agricultural drones were eliminated due to practicality. The remaining drone platforms were then narrowed down by the startup investment cost.

After eliminating many drone platforms due to price, the consultant then had to figure out what drone manufacture was best and what type of drone had the best sensor compatibility. Compatibility is a crucial component when considering a drone. The more sensors that are compatible with the drone, the more versatile the drone becomes. By narrowing down the drone platforms by compatibility and manufacturer reputation, very few platforms are left for consideration. At this point, it boils down to cost and the preference of the consultant.

The next step that was considered was what cameras and sensors would be appropriate for acquiring the precision data needed to generate an infestation field map. This was a short process because of a few concerns. First was cost, as stated in previous chapters, sensors often cost substantially more than the drone itself. Second, was a lack of knowledge towards what sensors would be best suited for imagery data collection and the software necessary to analyze it. This lack of knowledge in this particular area led to the decision of acquiring a drone with a RGB camera.

Figure 6.
Crop consultant deploying a drone with a RGB camera to capture aerial imagery of a wheat field infested with Wild oats in North Dakota, 2018
Courtesy of: C.R. Wynn

By purchasing a RGB camera, the consultant was hopeful that the color variation between wild oat and spring wheat would be detectable enough to process and make a precision map (Genik, 2015). After the drone and RGB camera were purchased, the consultant experienced drone anxiety. Just like many new consumers of drone technology, many are faced with learning a new technology and an investment that has the potential risk of being lost due to pilot error. This anxiety led to hesitation towards flying the drone by the crop consultant. After some time, and some encouragement from a seasoned drone pilot, the consultant was able to operate the drone and RGB camera without any supervision.

Once the consultant was comfortable operating the drone alone, it was time to start acquiring imagery data with the RGB camera (Figure 6). A free drone app, DroneDeploy, was used to assist in flying a precision grid throughout the field (DroneDeploy, 2019). An organized grid is very useful when attempting to stitch or mosaic many images together in the attempt of making a precision map. After many flights were completed from varying altitudes, the acquired images were analyzed to see if any variation between the wild oat and spring wheat was detectable. After analyzing the images, the consultant was disappointed with the results. No variation between the two plants was detectable when using a drone and RGB camera. When this conclusion was reached, additional flights were pursued at lower altitudes. Some of the flights conducted were as low as 15 feet from the crop canopy. After these low altitude flights were concluded, repeat analysis of the images were conducted. To the dismay of the crop consultant, little to no variation was detectable by these images and the possibility of a precision map was no longer probable (Lopez-Granados et al, 2016).

The use of the drone and RGB camera saw some promise in another agricultural management situation. During the same growing season, a few of the crop consultant’s

Figure 7.
Soybean plant with Iron Deficiency Chlorosis (IDC) with a rating of 2.
Source: NDSU Extension, 2017
From: Kendal H, 2018
Photo: T. Helms

growers were experiencing some plant health issues in their soybean fields. These particular soybean fields were experiencing symptoms of Iron Deficiency Chlorosis (IDC). IDC is a problem for soybean production and can drastically impact yield. The symptoms are interveinal chlorosis of the leaves with leaf veins remaining dark green (Figure 7). The enzymes involved in chlorophyll formation need iron, so when active iron (Fe) is low in leaves, chlorosis occurs (UMN, 2018). IDC in soybeans can be spread out randomly in a field. Being able to identify color variation, and possibly map the locations of IDC, would be extremely valuable.

The crop consultant deployed the drone in hopes of capturing the color variation between the chlorotic and healthy soybeans. After flying the iron deficient fields, the images were processed and analyzed. The imagery provided the consultant the needed information to calculate the amount of iron deficiency throughout the soybean field (Adams et al., 200). This imagery allowed the consult to accurately map the iron deficient areas for the grower, who then took the map and made a precision application of Soygreen liquid fertilizer. Soygreen is an iron (Fe) formula developed for soybeans and other crops suffering from iron deficiency chlorosis. The precision map led to a reduced application of Soygreen and resulted in a reduced application costs for the grower.

Conclusion

This particular case study illustrated many of the parameters growers, crop consultants, and agriculture businesses face when considering investing in drone technology. The iron deficient soybeans is an example of how drone technology could be implemented in obtaining additional knowledge for an in-season crop management decision. These two scenarios lay out ideal examples of how a similar approach in acquiring aerial imagery resulted in two different outcomes. While the imaging of IDC in soybeans turned out to be extremely beneficial, the outcome of the wild oat infestation, which was the intended reason of the drone purchase, produced disappointing results.

One of the main reasons the mapping of the wild oat infestation failed, can be attributed to the kind of camera used. The RGB camera used wasn’t able to pick up the color variability between the wild oat and spring wheat, even at a high resolution and infestation rate (Figure 8) (Lopez-Granados et al, 2006). By switching to a multispectral or hyperspectral camera discrimination between the wild oat would have been detectable according to their phenological stages (Figure 9) (Gomez-Casero et al., 2010). Even with the potential of success, by switching to a multi or hyperspectral camera, the crop consultant didn’t want to invest in an expensive spectral sensor that would have depleted any presumed marginal profit.

Drone and spectral technology has great potential for these two scenarios. The different reflectance data produced by a multi or hyperspectral camera or thermal sensor could have generated information that any grower, crop consultant, or agriculture business could have used in making a sound agronomic management decision (Gomez-Casero et al., 2010). Unfortunately, the RGB camera lacked the necessary capability, and the camera only proved successful in the iron deficient soybean field. Acquiring imagery from more than one spectral sensor would be ideal but highly unlikely for most. The price of investing in a drone and a single spectral sensor is enough to hinder many. The hurdles and obstacles that were discussed earlier will slow or stop growers and consultants from adopting drone and precision technology for agricultural use.

The biggest takeaway this chapter provides is the importance of matching the proper sensor to the right application. Research into the right sensor and application is extremely important. Learning about what has already been spectral or remotely sensed, and in what crops, will bring added confidence and education prior to any initial investment. By identifying the right sensor for the application, the risk of investment changes. While the initial investment may increase due to the sensor being acquired, applying the right sensor to the right scenario will increase the chances of profitability.

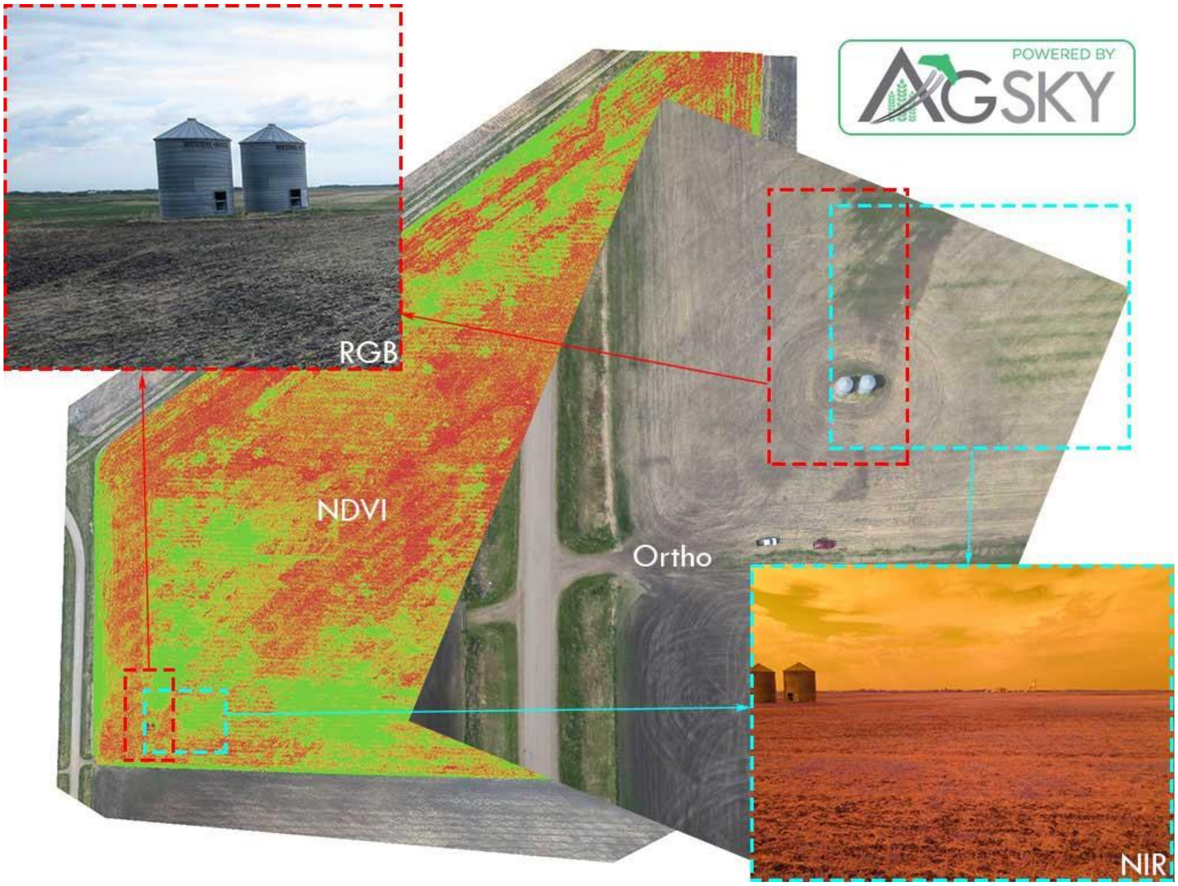


Figure 8. Variation between RGB and Multispectral (NDVI and NIR) imaging of wild oats
Used with permission: Green Aero Tech and AgSky Technologies

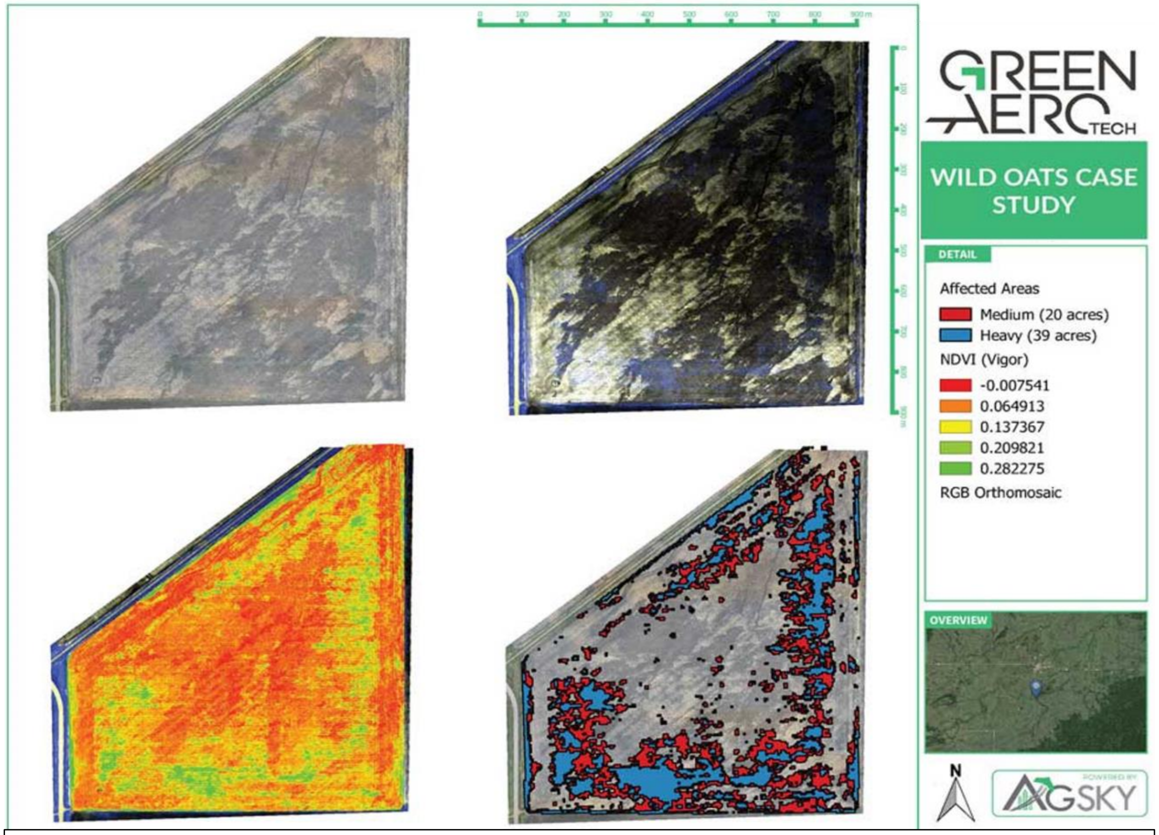


Figure 9. Precision mapping results from the RBG and Multispectral images acquired from a drone.
Used with permission: Green Aero Tech and AgSky Technologies

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CHAPTER 4

WHY IT’S TIME TO INVEST IN DRONE TECHNOLGY, AND WHY IT’S TIME TO WAIT

Introduction

As the human population increases every year, a higher demand for food quality and quantity becomes more prevalent. This notion puts added pressure on growers and agricultural production around the world. With advancements in technology like drones and spectral sensors, growers and agricultural businesses have an additional tool to meet these supply demands.

In the last century, aeronautics and aerial imaging has transformed the way the human race views this world and how we live our everyday lives. Drone and aerial imagery has evolved tremendously in the last decade. In the last 5 years, drone technology has been adopted by millions of consumers around the world. Drones, like many new technologies have seen a wide spectrum of usefulness. This spectrum involves areas like real-estate, construction, law enforcement, conservation, architecture, and agriculture.

As time progresses, drone and spectral technology will become increasingly more valuable and sought after. According to USDAs estimates, 6.6 million acres of U.S. Farmland has been lost from 2008 through 2015, with a 1 million acre decline in 2014 alone. The U.S. farming base has shrunk 7% in eight years, yet the world population is continuously growing. The U.S. Census Bureau is currently predicting that the world population will actually reach 9 billion by 2044. The United States is one of the world’s leaders in food production and is expected to grow from 322 million in 2015 to 389 million by 2050. With expectations of a higher population and the trend of farmland being lost, drones and spectral technology can help growers become more efficient and help them meet the food production demands of the future (Mayo, 2016).

Boots on the Ground or a Drone in the Sky

Drone use in agriculture has drastically improved in the last decade. Between the advancement in smart handheld devices and drone technology, the compatibility of the two technologies has forced many to look at incorporating drones as a management tool. While drone technology is both exhilarating and easy to use, there are many hurdles and obstacles for new consumers.

One of the biggest arguments that agricultural drone consumers ask is whether or not drone technology is a fancier, more expensive way to receive the same results as a crop consultant stepping into the field. Boots on the ground or a drone in the sky is a debate that is continually changing. The results of this argument often depends on how the technology is perceived. Many studies show that using drone images or pictures provides a more accurate measure of field conditions than even highly trained agriculture practitioners on the ground (Clifton, 2017). This perception often depends on the crop(s) being grown, the size of the field, and the management situations that are in place or that have worked in the past.

Past management decisions and how they were executed can take an effect on those considering drone technology. If scouting a field has worked in the past, and is still working, the thought of switching to drone technology may be minimal or nonexistent. The argument can then be made that scouting may be very effective, but too time consuming and less affective as using a drone. The human eye can only see in the visible spectrum, whereas a drone can carry a sensor covering multiple spectral ranges. Spectral sensors now allows one to see well past the visible range, which has proven to be valuable when looking at plant health throughout the field.

Drone and spectral technology can produce information that can result in better agricultural management practices. Something that’s often overlooked or misunderstood is the importance of matching the spectral data with true field conditions. Verifying these results or “ground truthing” will forever be necessary to make precise management decisions. Ground truthing involves the collection of measurements and observations about the type, size, condition, and any other physical or chemical property believed to be of importance concerning the plant health or field surface that are being spectrally sensed (Hoffer, 1972).

A big part of ground truthing is being able to analyze the information that is acquired by the drone. Proper analysis of the data is where many come up short. Acquiring the data is easy, interpreting the data correctly and agronomically is another thing. Sometimes, errors in data collection have caused ground truthing to become false data (Hoffer, 1972). By diagnosing and attributing the analyzed spectral data to the wrong plant disease or stressor, false information and spectral values are generated. This is a prime example of why plant practitioners and agronomist will forever be needed to bridge the gap of information between spectral imaging and crop health. For example, if a drone is used, and a spectral sensor delivers information where plant stress is detected in parts of the field, an agronomist will still be needed to bridge the gap to verify the cause of the plant stress.

Data collection is just one piece of the puzzle. Analyzing drone data can be an expensive and time consuming process. Many growers, crop consultants, and agricultural companies lack the ability to not only acquire the drone imagery, but also how to translate that information back to an agricultural platform. This often results in hiring or buying software from a company that helps in this process. This adds an additional cost to the initial investment of drone and spectral technology.

Future of Drone Technology

In 2019, Corteva Agriscience invested millions of dollars into drone and spectral technology. By doing so, they became the world's largest agricultural drone fleet. Through a collaboration with Cortevas Agriculture Division of DowDuPont, and DroneDeploy's advanced mapping software, a fleet of more than 400 drones are being used across the company worldwide (DroneDeploy, 2019). This major investment has given Corteva the ability to generate immediate insights to diagnose and correct agronomic, disease, and pest concerns, as well as to suggest locations for optimal product placement (DroneDeploy, 2019). Matt Kurtz, a Global Seed Technologist with Corteva Agriscience said this about the investment of drone and spectral technology: "We are aggressively evaluating and implementing decision agronomy tools like drones and spectral sensors to enable our agronomists and contract seed growers to make timely decisions impacting seed yields and quality" (DroneDeploy, 2019).

By utilizing drone and spectral technology, a grower or business can now scout a field more efficiently and in a matter of minutes. In less than 15 minutes, advanced drone technology can survey a 160-acre field to identify variations in plant health, giving growers direct access to real-time aerial views and data to help make informed agronomic decisions (DroneDeploy, 2019). While flying fields is a fairly quick process, it's the spectral imaging analysis stage where the bulk of time and investment comes into play (DroneDeploy, 2019). There's often a misconception that drones will save large amounts of time; this is wrong. Analyzing the data takes just as much time to analyze, as scouting a field traditionally would (Eckelkamp, 2018). Although, the time that is spent is more effective and efficient than traditional scouting (Eckelkamp, 2018).

Depending on the size of the growers operation, the drone and spectral sensor being used, as well as the drone's flight time, a grower could scout a 640 acre field in approximately two hours or less. This real-time imagery and analysis will allow for more efficient management decisions, which will directly impact plant health and yield (Raun and Johnson, 1999). As crop management plans become more efficient, time conservation and allocation can be placed in more demanding areas.

Flying an entire growing operation in a matter of hours allows the grower to surveil fields as often as they see fit. Detecting mechanisms that affect plant health in the earliest stages is key to control and containment. The earlier you catch the problem, the cheaper it is to contain it. With food production needing to double by 2050, being able to recognize and prevent plant health issues at their earliest stages will become increasing critical in order to feed a growing population (FAO, 2009).

The University of Nebraska is tackling this future problem head on by incorporating new technology to make better management decisions and fertilizer applications. The Nebraska On-Farm Research Network is a project focused on improving the efficiency of nitrogen fertilizer use. Project SENSE (Sensors for Efficient Nitrogen Use and Stewardship of the Environment) implemented 20, on-farm research sites, starting in 2015 (Thompson, 2015). Project SENSE uses multispectral sensors to determine the health of a plant throughout the growing season.

Figure 1. Project SENSE crop sensor in a corn in Nebraska
Source: UNL Institute of Agriculture and Natural Resources Cropwatch
Source: Thompson, L

The way these multispectral sensors work is by being positioned over the corn row (Figure 1). The sensors then emit modulated light onto the crop canopy. Photo detectors on the bottom of the sensor measures the light that's reflected by the leaf. Specific wavelengths of light are measured, in this case red, red-edge, and near infrared light. The wavelength information is recorded by the crop canopy sensor, and the Normalized Difference Red Edge index, or NDRE, is determined.

The NDRE index has been correlated to a specific property of the crop, in this case nitrogen status (UNL Extension, 2018). That index is then transformed via algorithms into a recommended rate of additional nitrogen fertilizer to be applied. Sensors mounted on an applicator boom can measure the nitrogen status in real time as the applicator moves through the field, while the applicator applies the needed nitrogen in real time. Seventeen field sites were selected in 2015. These sites were located within 5 natural resource sites (NRDs), where groundwater nitrate measurements are at critical levels.

In two growing seasons, Project SENSE had positive results. In one particular study, located in Nance County, Nebraska, a corn grower applied a total of 145 pounds of nitrogen per acre (N/acre) on one of their fields. The multispectral sensors that were used for the study was able to determine if additional nitrogen was needed in varying locations in the field. Project SENSE made an additional nitrogen application of 44 pounds per acre. This efficient management approach resulted in a 10.5 bushel per acre yield increase when compared with the growers' nitrogen management strategy. Additionally, the Project SENSE nitrogen management strategy resulted in a $15 per acre higher marginal net return than the growers management plan (UNL Extension, 2017).

Figure 2. Project SENSE launches an eBee SQ drone during a demonstration on Aug. 16, 2017.
Source: UNL Agronomy and Horticulture Annual Newsletter 2017, p.17.
Photo Credit: Barrett Stinson, Grand Island Independent

Project SENSE has also incorporated drone technology into their research. UNL is using a fixed-wing drone equipped with the same type of spectral sensors used on their tractor applicators (Figure 2). The drones are fully automated and their flight paths can be planned shortly before application. The sensors on the drone can photograph the near infrared spectrum, which gives the farmer additional information about the crop's canopy structure, the health of the leaves, and whether or not they are stressed (Pore, 2017). Joel Crowther, a UNL graduate student working on Project SENSE, said this about using a drone platform for the spectral sensor: “The other beneficial thing sensors have that our eyes can’t, is the ability to quantify or put a number to that stressed plant, this is extremely useful when managing the crop properly.” The information that can be provided by these sensors can help growers identify the area of the field where the crops need assistance the most (Pore, 2017).

Crowther also stated: “If drones can do just as good of a job as the tractor based sensor, then there are so many more applications for these drone sensors because of their timeliness and their availability is a lot better than actually having to drive through a field.” There are numerous opportunities for drone use in crop production. According to Ag Technologies Nebraska Extension Educator, Laura Thompson, multispectral sensors that can be mounted on drones are an exciting technology that can provide new insights into crop condition and stresses (UNL, 2017). The total economic impact of unmanned aerial systems (drones) integration in just the state of Nebraska is projected to reach $149 million by 2025, according to a 2013 report by The Association for Unmanned Vehicle Systems International (AUVSI, 2013). According to conservation estimates as stated by the AUVSI report, U.S. annual sales of drones in agriculture is expected to reach 160,000 units by 2025 (AUVSI, 2013). Actual sales could be far greater (UNL, 2017).

The future of drone technology is exciting and has a lot of room for improvement. Currently, growers and crop consultants that can afford drones and spectral sensors are using them more as a reactive management tool for their fields. Making the transition from a reactive tool to an active tool, is where the future of drone technology lies (Karpowicz, 2016). Being able to see the early development of a noxious weed, plant pathogen, or other biotic plant stressors, is what can make the adoption of this precision tool accelerate.

If there's going to be an improved rate of adoption and application for drone technology in the next decade, additional research and investment is essential. Developing a better understanding and building a spectral library of all major plant pathogens, weeds, agronomic insects, and other biotic factors is needed (Zomer et al., 2009). Success in building this spectral library falls on the procedures involved in the collection of surface observations (Clark et al, 2007). This must be accomplished with extreme care in order to define the appropriate reflectance values and to not falsify the information being observed on the ground. This is one reason why plant practitioners and agronomists will forever be needed, regardless of where technology goes in the future.

To achieve a spectral library, it's going to take a substantial amount of funding and research on a global scale (Zomer et al., 2009). If this is accomplished, our ability to more effectively manage the agricultural environment will become more efficient and sustainable, and feeding a growing population will be attainable.

Is Drone Technology Worth the Investment

Drone technology has seen some amazing applications in agriculture. Today, these applications are being utilized by many individuals, universities, and companies around the world. A solid majority of those acquiring drones for agricultural purposes are large industrial companies, precision aerial mapping businesses, and universities for research purposes (Reagan, 2017). With larger budgets and business plans that incorporate drone technology, it makes sense that these larger firms are quicker to adopt drone technology. But what about the everyday grower and crop consultant, should they invest in drone technology right away?

Chris Neeser asked a similar question in 2014. Nesser, a research scientist with Alberta Agriculture and Forestry’s Crop Diversification Centre, wanted to know what drones could and couldn’t do and their cost/benefit as a scouting tool were. Nesser wasn’t alone with these types of questions, a lot of growers and agriculture businesses wanted answers too. In a short period of time, Nesser received funding from seven organizations. What prompted Neeser to do this research was the increased marketing of drones to growers as the new “must-have” farming management tool. Many agricultural businesses were trying to offer growers NDVI precision maps that “could show you what’s really happening in the fields” (Nesser, 2016).

Much of the marketing being sold was that drones could generate precision maps quickly and easily, allowing growers to get a bird’s-eye view of their fields to identify areas that need attention and take quick action (Nesser, 2016). What Neeser and his team found, however, was a process a bit more complicated than that. In order to generate a quality precision map, many factors need to be taken into consideration. These factors were: the stability of the drone in windy conditions, the flight controls, the camera’s quality and capability, keeping the camera lens clean and free of debris, and finally, the software and technical ability to process the collected data into a readable, high-resolution precision map (Nesser, 2016).

The research team used a fixed-wing drone and captured images three times during the season in six crops (two fields each of barley, canola, field peas, seed alfalfa, potatoes and spring wheat). The first flights, conducted in late May and early June, were focused on weed scouting, while the second two flights (late July and mid-August to early September) assessed the ability to spot crop diseases from the drone (Stanfield, 2017).

After three growing seasons, Nesser had some answers. Identifying weeds with a drone severely lacking, the resolution of the sensor just wasn't high enough to detect weeds in their earliest stages. Nesser explained that at an altitude of 600 feet, the variability was completely washed out and the NDVI formula became useless (Nesser, 2016). He further stated that flying at a lower altitude still didn't solve this issue. At lower altitudes, being able to identify weed seedlings verse the crop seedlings became distorted within the image pixel, making it nearly impossible to correctly identify different plants.

Nesser was more successful when it came to spotting plant disease within a field. Crop disease(s) tend to create patches that are highly visible in the crop canopy from a higher altitude (Stanfield, 2017). Neeser thinks growers could use those images to guide boots on the ground to physical inspections and treatments of that location. In some of the canola field's, clubroot (*Plasmodiophora brassicae*) was detected. By flying the drone over the field, patches of the disease was located and then identified.

While Nesser and his team found success in locating plant diseases in some of their research fields, he had a word of advice: "With crop diseases, we have enough resolution to see it's there, but it can't tell us what the disease is" (Nesser, 2016). Neeser's advice echoes the importance of boots on the ground and how crop consultants and agronomist are still needed to ground truth the information being seen.

According to Neeser's research, is it worth investing in drone technology? The answer is yes and no. He explains that drones and all the imaging software needed to support and create a precision map is a major investment. Neeser stated that currently, there's no way a drone can compete with a satellite on cost, but they can help each other. Most of the drones being flown on farms right now is a result of "a grower being intrigued by them; then they find an application for them" (Neeser, 2016). Neeser explained that drone technology is right where the computers were in the 1980s, it's in its infancy, but after some more investment, research, and time, drones will become a major part of agriculture in the future.

Now, more than ever, growers and crop consultants have to deal with increasingly complex concerns. Many of these concerns fall under the realm of water quality and quantity, climate change, herbicide-resistant weeds, soil quality and erosion, uncertain commodity prices, and increasing input prices to name a few (Agribotix, 2018). Growers, crop consultants, and agricultural businesses are starting to turn to high-tech management tools, often under the banner of precision technology or precision agriculture. They are doing so to respond to, and mitigate, these growing concerns. Drone and precision technologies are helping growers and agricultural business outline better management strategies for these complex issues. These technologies can be combined with yield monitors, soil sample results, moisture and nutrient sensors, and weather feeds. This can help growers and crop consultants to dig deeper into a field's profile while building a more heterogeneous field strategy.

In-season data is one of the most valuable pieces of information a drone and precision program can provide (Agribotix, 2018). With this data, a grower can spot problems early and rapidly select appropriate interventions. Additionally, a drone gives the grower the ability to access new field data whenever they see fit. It’s this capability where drones outcompete satellite and manned aerial imagery. Satellites and manned aerial flights are often hindered by cloud cover, inclement weather, and time availability. Satellites are equipped with sensors that are best suited for surveying tens of thousands of acres at a time, and the incumbent data that’s generated becomes a one size fits all assessment. Satellite data can provide some level of spatial management information within a field and the resolution is improving (Barsi et al., 2014). Satellite imagery is better and faster than it once was and is far less expensive than drone spectral imaging (Neeser, 2016). However, it currently does not provide the resolution a drone or manned aircraft can provide (Barsi et al., 2014).

Drones are becoming more affordable every year (Neeser, 2016). This lowered cost is making the initial investment more attainable to the average grower. When compared to other pieces of farming equipment, drones are a very modest capital investment. Often, those curious about investing in drone technology want to know how fast they’ll see a return on the investment. According to major drone makers and precision agriculture companies like: PrecisionHawk, DJI, Corteva, DroneDeploy, and Agribotix, a drone can pay for itselft and start saving the grower money within a single growing season. For high value crops that are prone to disease, such as potatoes, citrus, almonds, and bananas, the financial benefit and return on investment could be significantly higher and much faster (Agribotix, 2018).

Drones are still considered a new tool for agriculture and spectral sensors still have their limitations. Many questions still have to be answered to make this tool a feasible investment for all agricultural producers. If a grower has a common plant disease, pest, water issue, or a fertilizer deficiency, then drone technology has already proven worthy in those areas. But with new or uncommon plant health issues, drones and spectral technology comes up short. Not because it can’t obtain the information needed to sense these issues, but because the spectral sensing research has not been accomplished for that particular plant disease, deficiency, or stressor.

If a grower wishes to use a drone to identify a specific disease, weed, or an insect that’s a significant problem, drone and spectral technology may not be the most cost effective investment at this time. As mentioned earlier, spectral sensors are very expensive and the average grower and crop consultant will not have the financial means to justify such a purchase. High value crops may help in this investment, but the right sensor still needs to be identified for the application. Investing in drone technology usually boils down to four things, the crop(s) being grown, the size of production, the liquidation of finances, and the genuine interest the grower has in precision agriculture.

Conclusion

From the days of Joseph Niepce and the Wright brothers, and to our current time, aerial imaging has played a pivotal role in the lives of human beings. With the advancements in technology, aerial imaging has evolved to the point where it has started to benefit agricultural production. These benefits can be mostly attributed to spectral sensors that were developed to see in all areas of the electromagnetic spectrum.

Being able to see well beyond the visible range, growers now have the ability to detect plant health issues throughout their fields and can create better management strategies for individual fields. This heterogeneous approach is becoming increasingly more important as the world population increases every day. Unfortunately, this approach is being slowed down by the current prices of spectral sensors.

As the human population expands, the demand for food and shelter will increase. These demands will put added pressure on growers to produce more food with less land in the following years. With the help of precision tools like drones and spectral sensors, the grower now has the capability to detect plant health issues earlier than they ever have before. Depending on the application needed, multispectral, hyperspectral, thermal, RGB, and LiDAR sensors all possess unique capabilities that can benefit the grower throughout the season.

While many benefits of using drone and spectral technology have already been discussed throughout this document, it’s important to understand that not all growing situations are identical. Growers around the world are faced with different growing environments, soil types, water availability, insect pressure, and other biotic stressors unique to their growing operations. This variability will also determine if investing in drone technology is economically feasible.

The relationship between drones and spectral sensors is still in its infancy stage. With more investment, research, and time, drones and spectral technology will become a major agricultural management tool in the future. As drone and spectral sensor prices change yearly, a grower’s ability to invest becomes more attainable (Wile, 2017). As more growers around the world find that a drone provides a more efficient way to identify problems in their field, adoption percentages will rise continuously. With no sign of change in drone regulation or grower abatement, it makes sense to seriously consider any technological management tool that can boost productivity, mitigate input costs and ultimately, improve the bottom line.

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