Aerospace technology generally refers to the development and utilization of aircraft, satellites, space vehicles, and peripheral equipment including sensors. A notable development in aerospace technology includes unmanned aerial systems (a.k.a. drones) and associated policies that allow agricultural practitioners and researchers to use the technology safely and legally (Kim et al., 2021). Along with aerospace technology, geospatial technology is used to collect, process, analyze, and present geospatial data (Park et al., 2007). The technology generally involves global...
positioning systems (GPS), geographical information systems (GIS), and remote and proximal sensing (Park and Tollefson, 2005). The use of aerospace and geospatial technologies together has created a novel and attractive tool, and these technologies indeed have been transforming agriculture during the past 20 years (Park et al., 2018; Filho et al., 2020).

When aerospace and geospatial technologies are used for pest management, each technology exhibits advantages and disadvantages. Satellites can monitor pests in large geographic areas such as countries and provinces, while their spatial resolution may not be high enough to detect minor or local pest damages (Moran et al., 1997). Manned airplanes can achieve regional-scale pest surveys and also apply control measures such as pesticides; however, it carries a risk of a crash, which can cause human or property losses (Park et al., 2018). Alternatively, small drones offer safe and versatile tools for orchard-scale pest surveys and also can apply control measures site-specifically within an orchard (Filho et al., 2020). However, large-scale pest monitoring or application of control measures with drones is still very challenging in many cropping systems. Specifically, aerospace and geospatial technologies have not been widely adopted for apple IPM, although numerous previous studies have been conducted in other cropping systems for pest detection and management (Mogili and Deepak, 2018; Zhang et al., 2019; Filho et al., 2020).

This article reviews and presents the potentials and limitations of aerospace and geospatial technologies (i.e., satellite, drone, remote sensing, and information system) for apple IPM. By using a case study in apple orchards, this article addresses (1) monitoring and survey of pests by using satellites, drones, remote sensing, and GIS, (2) application of control measures by using aerospace technology, and (3) potential of artificial intelligence and machine learning to apple IPM. The aerial imageries of satellites and drones presented in this article were collected in 2018–2020 at the Korea Apple Research Institute (KARI) located in Gunwi, Republic of Korea. The KARI was founded in 1991 under the Rural Development Administration of the Republic of Korea (Fig. 1) with the missions of apple research include breeding, production systems, and IPM.

Application of Remote Sensing Technology for Pest Detection in Apple Orchards

Remote sensing provides a possible solution to extensive and intensive pest surveys at multiple spatial scales (i.e., from continents to individual plants) in a timely manner (see Fig. 1 for example). In general, remote sensing in agriculture uses optical sensors onboard a satellite, aircraft, or drone without physical contact with target crops (Lillesand and Kiefer, 2000), which can provide information about the physical and physiological condition of crops (Bauer, 1985; Curran, 1985; Clevers, 1999). The optical sensors include, but are not limited to natural-color, near-infrared, multi-spectral, hyperspectral, and thermal sensors. Spectral or optical resolution varies depending

**Fig. 1.** Example aerial imageries acquired with various aerospace and geospatial technologies. A, Landsat satellite imagery around the Korea Apple Research Institute (KARI, red box); B, SPOT satellite imagery of the KARI (outlined); C, a composite drone image of a specialty-apple plot in the KARI; D, a high-resolution image of the canopy of an apple tree.
on the flight altitude, weather, and sensors used to obtain the data or imagery. Common multispectral imagery includes wavelengths in the visible (380–700 nm), infrared (700–1,400 nm), and thermal (> 1,400 nm) ranges. Earlier entomological studies (Brewster et al., 1999; Fitzgerald et al., 2004; Yang et al., 2005) indicated that remote sensing would offer many potential benefits to growers and should continue to be an active area of research for many years. However, there have been relatively few published studies regarding pest detection in apple orchards by using remote sensing. Here, we review the use of aerospace and geospatial technologies related to apple IPM with a case study conducted at the KARI with remote sensing using satellites, drones, sensors, and geographic information system (GIS) to detect insects, plant diseases, and weeds in apple orchards.

**Remote Sensing with Satellites**

Satellites have been widely used for remote sensing to conduct large-scale crop monitoring (Moran et al., 1997). For example, Landsat satellites carry multiple sensors, including natural color (i.e., RGB), near-infrared (NIR), and thermal sensors. The sensors can be used to detect spectral reflectance from vegetation that is significantly influenced by leaf pigments, cell structure, and cell water content (Jensen, 1983). Reductions of pigments (i.e., chlorophylls $a$ and $b$, anthocyanin, and carotenoids) in plant tissues could be associated with herbivorous insects. Changes in the amount of the pigments could be detected by using a vegetation index, a combination of remotely-sensed imageries at different wavelengths. The most commonly used vegetation index is the normalized difference vegetation index (NDVI). The NDVI values range from -1 to 1 and correspond to the condition of vegetation; low values correspond to barren fields, moderate values represent shrub and grassland, and high values indicate dense vegetation. For example, NIDVI is generated by using imageries from both NIR and red lights (Fig. 2A and B). Differences in NDVI values between 2019 and 2020 maps of apple orchards in the KARI (Fig. 3C) showed an increase of NDVI values (i.e., blue pixels) in some apple plots, indicating vegetation condition improved from 2019 to 2020. The change can be further investigated and confirmed with drone imagery (Fig. 3D), thermal imagery (Fig. 3E), and NIR imagery (Fig. 3F). These maps can

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**Fig. 2.** Normalized difference vegetation index (NDVI) maps of the KARI (outlined) in May 2019 (A) and May 2020 (B) generated by using remotely sensed data by MODIS sensors equipped on Landsat satellites. The difference of each pixel in A and B was calculated to determine changes in vegetation between the two years (C; higher values indicating improvement of vegetation from 2019 to 2020). RGB (D), thermal (E, relative surface temperature), and NIR (F) sensors were used to generate additional aerial images to further examine the changes in land use and vegetation. Black arrows indicate a specific apple plot of which vegetation index was increased between 2019 and 2020.
be used to determine a large-scale change of vegetation in multiple apple orchards and to identify areas for more detailed surveys with drones or ground-truthing.

Remote sensing with satellites has multiple advantages for apple IPM. Satellites with various sensors orbit the Earth regularly and repeatedly (e.g., Landsat satellites 7 and 8 repeating their orbital pattern every 16 days), and thus a planned large-scale pest monitoring is possible. Two major disadvantages would be a limited spatial resolution (e.g., the spatial resolution of Landsat satellites in Figs. 1 and 2 is 30 m by 30 m) and weather-dependent image quality (e.g., cloud cover). Currently, three Korean government agencies (i.e., Rural Development Administration, Ministry of Science and ICT, and Korea Forest Science) plan to launch a satellite for agriculture and forestry in 2023, which could help a large-scale apple pest monitoring and IPM in the Republic of Korea.

Remote Sensing with Drones

There are two types of drones: fixed-wing and rotary-wing drones. Fixed-wing drones are similar to a typical manned airplane which can fly longer distances and survey larger areas. A rotary-wing drone possesses excellent maneuverability with the capability of hovering, but it had limited endurance and speed (Park et al., 2018), making it suitable for small-scale remote sensing. A typical operation protocol for an aerial survey with drones to detect pests includes planning a flight path and survey altitude, operating drones with autopilot function, downloading aerial imagery, stitching images, georeferencing the imagery (Fig. 3A), and analyzing aerial imagery to detect pests. Using the protocol, detection of great plantain (*Plantago asiatica* L.), a dominant weed species on a pre-planting apple plot at the KARI, could be achieved with a rotary-wing drone (Fig. 3B and C).

Aerial survey with rotary-wing drones equipped with an object-detection sensor or collision-prevention sensors can achieve a closer and targeted survey in apple orchards. An aerial survey at the KARI demonstrated that detection of plant diseases on individual apple trees would be possible using a rotary-wing drone. Two major apple diseases at the KARI were investigated by using a thermal camera, and the results of the survey showed that anthracnose on fruit was not detectable with a thermal sensor, but *Marssonia* blotch on leaves was readily detectable because infected leaves exhibited 2–3°C higher temperature than healthy leaves (Fig. 4). This might be caused by the fact that infected leaves generally reduce transpiration and thus leaf temperature increases (Taiz and Zeiger, 2006). Thresholding (i.e., changing values of temperature threshold) for disease detection readily extracted infected leaves from healthy leaves (Fig. 4), suggesting that automatic detection using image analysis is possible. Such thermal imaging also can be used to detect flying insects. The idea is based on the fact that the body temperature of a flying insect increases due to the movement of flight muscles (Chapman, 1999). Therefore, it may not be able to detect when an insect is not using flight muscles but can detect when it is flying (Fig. 5).
Remote sensing using drones has multiple advantages for apple IPM. The case study at the KARI suggests the possibility of site-specific or individual tree-level pest detection and management. Detecting changes in the tree canopy in the orchards over a period also can be achieved by repeated flights of drones. However, large-scale remote sensing could be challenging due to the limitations of battery life and flight regulation (e.g., visual line-of-sight rule).

**Geographic Information System (GIS)**

GIS is a geospatial technology for creating and managing spatial data and associated attributes (Park and Tollefson, 2005). GIS can integrate data collected in different times, at spatial scales, and with various sensors (Park et al., 2007). In the early stage of GIS development, the main method to create GIS data was digitizing, manually entering, and scanning spatial data or maps. However, recent GIS data can be commonly acquired with remote sensing by using satellites and drones, creating interactive queries, analyzing spatial information, and editing data (see Figs. 1–2 for an example).

A report by the National Geospatial Advisory Committee (NGAC, 2016) envisioned four emerging technologies in GIS. These include real-time spatiotemporal data creation and interaction, miniaturization of technologies, the proliferation of...
new mobile geospatial sensor platforms, expanding wireless and web networks, and advances in computing speed and capacity for geospatial research and applications. Based on the current trend of information technology, data analytics and mobility of GIS continue to grow and thus, the future GIS may include virtual reality, 3D GIS, mobile GIS, and Internet of Things (IoT). A good example would be current research efforts at the KARI on establishing a smart farming system in apple orchards using IoT and big-data-driven models (Fig. 6).

**Artificial Intelligence**

Since artificial intelligence (AI) was founded in 1955, AI development has been focused on reasoning, planning, learning, natural language processing, perception, and manipulating objects (Russell and Norvig, 2020). Among them, machine learning (ML) uses computer algorithms to improve automated self-learning by using training and validation data (Wang et al., 2019). There are three main approaches in ML: supervised, unsupervised, and reinforcement learning. In supervised learning, the computer learns a general rule that maps inputs to outputs with training data and labeling or annotation (e.g., detecting target pest) (Hastie et al., 2009). No labels are given to the learning algorithm in unsupervised learning, but the computer finds the structure or pattern by itself (i.e., distinguishing crop damage by multiple pests). Therefore, unsupervised learning is generally used to discover hidden patterns or features in data (Russell and Norvig, 2020). Reinforcement learning makes computer programs interact with a dynamic or changing environment (e.g., pest outbreaks in various environments). In
In addition, the deep learning technique mimics the human brain in processing unstructured and unlabeled data. Using deep learning, automated detection of insect pests (Roosjen et al., 2020; Rustia et al., 2021), plant diseases (Hasan et al., 2020), and weeds (Wang et al., 2019) could be achieved. However, there have been no studies published on the use of deep learning for apple IPM pest detection yet.

Application of Control Measures using Aerospace Technology

Chemical Control

Airplanes have long been used to apply pesticides in large areas since the first airplane was invented. The prolific use of a manned airplane to apply pesticides after World War II is still the main tool for large-scale pesticide application in production agriculture and forestry (Felsot et al., 2010; Heidary et al., 2014). Recently, rotary-wing drones have drawn attention for pesticide and fertilizer applications (Mogili and Deepak, 2018), which opened up an opportunity for aerial site-specific chemical control. In general, a decision for pesticide application is based on the economic threshold; when the average pest density is above the economic threshold, a pesticide is applied in the entire field. In contrast, site-specific pest management determines the location of pest control within a field than uniform pest control the field (Park et al., 2007). One of the major advantages of site-specific pest management is the ability to reduce insecticide use because applications are made only to a part of the field only where pest control is needed. With rotary-wing drones, site-specific application of pesticides can be realized in apple orchards.

Biological Control

Since the use of aircraft to release natural enemies was first suggested by Herren et al. (1987) several aerial-release systems using manned aircraft have been developed (Rosenthal, 2017; Carroll et al., 2008). Park et al. (2018) developed drones equipped with an aerial system for the precision release of natural-enemy insects to control invasive plants. The aerial-release system comprises a pod carrying biocontrol agents and a dispenser that releases each pod while in the sky (Fig. 7). A recent improvement of the system included a 3D-printed pod made of environmentally-friendly materials such as polyvinyl alcohol (Kim et al., 2021). Recent advances in drone technology have created new opportunities to reduce application costs and increase coverage of areas compared to manual distribution (Filho et al., 2020). Research on the aerial release of predatory mites to control spider mites has been attempted, but more research needs to be done for apple IPM.

Conclusion

Aerospace and geospatial technologies together have already been transforming agriculture. Such technologies could be used to accurately detect and monitor pests, make management decisions, and apply control measures for apple IPM. Mini-
turization and high accuracy of GPS, along with desktop and web GIS, have already revolutionized the ability to understand the spatial patterns of pest populations, which enables site-specific pest management to increase control efficiency with reduced pesticide input for apple IPM. Remote sensing of pests has become a common tool and GIS technology has become more affordable, which could be incorporated into apple IPM. Further development of such technology will be empowered by AI and IoT for automation of pest detection and decision making for apple IPM (Fig. 6).

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