Plant functional remote sensing and smart farming applications

Kenji Omasa[1,2*], Eiichi Ono[1], Yasuhiro Ishigami[1], Yo Shimizu[1], Yoichi Araki[1]
(1. *Faculty of Agriculture, Takasaki University of Health and Welfare, Gunma 370-0033, Japan*;
2. *The University of Tokyo, Tokyo 113-8657, Japan*)

Abstract: Plants have the distinctive 3D spatial structure that varies among organs, species and communities, and the spatial structure changes as they interact with their environments. The functions linked to fundamental biological activities such as transpiration, photosynthesis, and growth are also affected by the spatial structure and the environment. In order to promote smart farming using information and communication technology (ICT), it is necessary to measure and utilize information at the cell-organ of plants to the individual and the community levels and the environments in two or even three dimensions. Therefore, this paper introduced the outline of remote sensing of plant functioning and examples of the 3D remote sensing from relatively short distances using drones and ground Lidar. The quality control of rice in the paddy field and chlorophyll fluorescence imaging for photosynthetic diagnosis were also introduced. In addition, a field smart farm and a smart greenhouse, which heavily utilize ICT, built at Takasaki University of Health and Welfare in Gunma, Japan, were also introduced.

Keywords: remote sensing, smart farming, smart greenhouse, IoT, ICT, image analysis
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1 Introduction

Plants have a distinctive 3D spatial structure that varies among species and organs, and this spatial structure changes as they interact with their environment. The functions related to basic biological activities such as transpiration, photosynthesis, and growth are also affected by this spatial structure and the environment[1-4]. Therefore, in order to promote smart farming using information and communication technology (ICT), it is necessary to measure and utilize information at the cell-organ or individual level and the environment of plants in two or even three dimensions. Information on plant structure and functioning is useful to achieve the optimization of smart and sustainable farming systems and plant breeding systems. Remote sensing, developed for satellite-, air-, and vehicle-borne (including UAV), handheld and network sensors, is a key technology for obtaining spatial-temporal information, noninvasively. Technical trends in remote sensing are hyper-spectral, hyper-spatial, high-frequency or continuous, active, 3D, composite, application of network-use, and model assimilation with observations.

Since the mid-1970s, we have studied remote sensing in plant structure and functioning[1,2,5-20]. The study was initially focused on the development of digital instrumentation system using multiband cameras in visible to near-infrared and thermal regions. This system was used for quantitative image analyses of plant functioning such as stomatal response, transpiration, gas exchange, plant pigment contents, visible injury and plant growth in the climate-controlled greenhouse and experimental farm using analog and optical network systems around 1980, and then it has been expanded into aerial and satellite remote sensing. Before the mid-1980s, the study was developed into direct observation of stomatal response of attached leaves and the first MRI observation of spatial difference in root-soil water content in potted plants. Around the mid-1980s, the study was advanced in the first development of active chlorophyll fluorescence imaging system for photosynthesis analysis of attached leaves, and then it has been expanded to the 3D microscopic imaging research and solar-induced fluorescence one. In the first half of the 1990s, we started to study 3D plant structure and functioning using both passive and active techniques and around the mid-1990s, the technique shifted to 3D active remote sensing of plants and their communities using air-borne and ground-based Lidars. Since the 2000s, the air-borne (including UAV) and ground-based passive and active systems have been applied to research on plant sciences, plant phenomics, agriculture, and environmental monitoring, etc. In addition, we have progressed in composite remote sensing research by combining passive and active 3D, hyperspectral and multiband cameras, thermal camera, chlorophyll fluorescence imaging system, etc.

As part of smart farming, smart greenhouses are attracting attention. A state-of-the-art smart greenhouse which heavily utilizes ICT has been operational since 2019 at Takasaki University of Health and Welfare in Gunma, Japan. A one-hectare smart farm consisting of a smart greenhouse, a field plot, a rice paddy field plot, and a multipurpose area has been completed on the adjacent location to the north of the Faculty of Agriculture building. One of the features of the farm is that it is wired and wirelessly connected to the university LAN (Local Area Network) and mobile

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Biographies: Eiichi Ono, PhD, Lecturer, research interests: 3D remote sensing and smart agriculture, Email: ono-e@takasakaki-u.ac.jp; **Yasuhiro Ishigami**, PhD, Associate Professor, research interests: horticulture and horticultural engineering, Email: ishigami@takasaki-u.ac.jp; **Yo Shimizu**, PhD, Professor, research interests: GIS, remote sensing, terrestrial ecosystem, phenology and climate change, Email: shimizu-y@takasaki-u.ac.jp; **Yoichi Araki**, PhD, Professor, research interests: breeding and cultivation of strawberry plants, Email: araki-y@takasaki-u.ac.jp.
*Corresponding author: **Kenji Omasa**, PhD, Faculty Dean and Professor, research interests: functional and 3D remote sensing, plant phenotyping and smart agriculture. Faculty of Agriculture, Takasaki University of Health and Welfare, 54 Nakaorui-machi, Takasaki, Gunma 370-0033, Japan. Email: omasa@takasaki-u.ac.jp; aomasa@mail.ecc.u-tokyo.ac.jp.

communication network, allowing for education and research using ICT. For example, in addition to the measurement and control of the greenhouse environment, one can constantly monitor the crops and growth environment in the field using drones, various image sensors, and weather observation stations. Such information can be used for crop diagnosis, cultivation management, and plant phenotyping.

2 Remote sensing of plant functioning and structure

Figure 1 shows a conceptual diagram of remote sensing of plant functioning. As shown in the figure, there are various types of remote sensing of plant functions, ranging from the leaf level to individual plants, plant populations, and even vegetation in a wider area. Remote sensing over a wide area involves analysis of soil and other geospatial information. However, we limit our discussion to remote sensing of plant functions over a relatively short distance, which is closely related to smart farming. In the case of short distances, the terms "image measurement" and "imaging" are often used, but the term "remote sensing" is used in this paper.

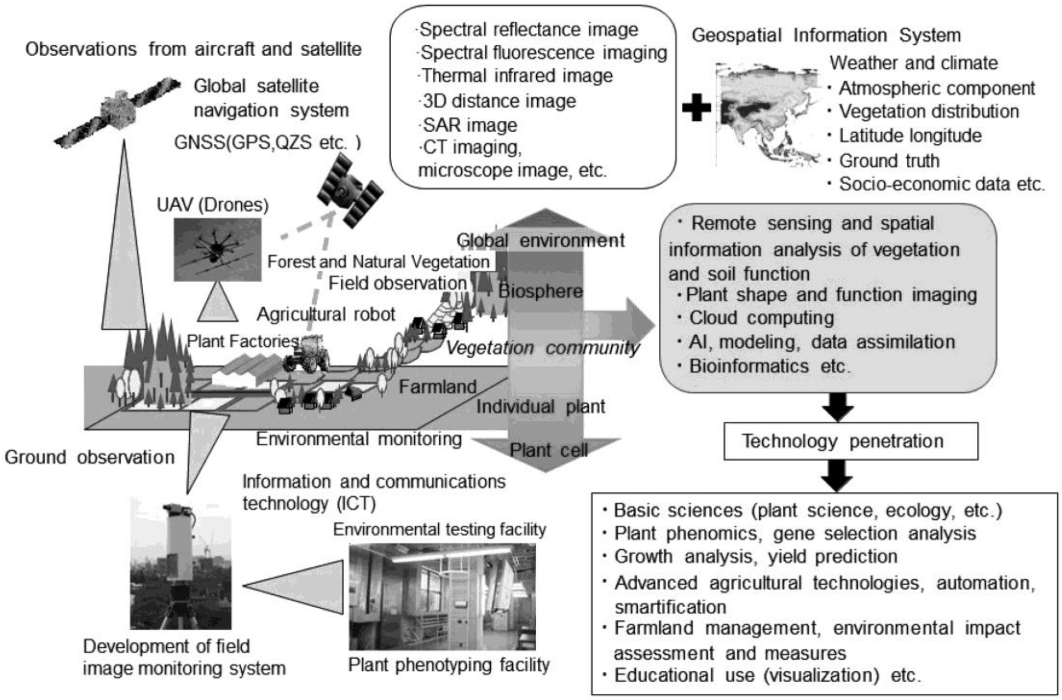


Figure 1 Concept of remote sensing of plant functioning and structure[15]

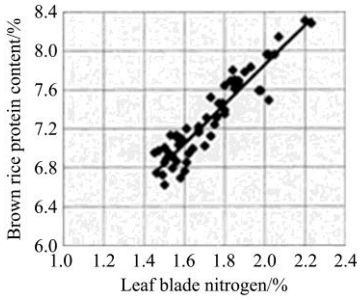
In the research field, which is the basis of smart farming, image information is used to elucidate plant functions, analyze environmental responses, analyze and screen genes, which to search for biologically meaningful genes and compounds among a large number of genes. In particular, in the field of plant phenomics, remote sensing of plant functions has recently been actively implemented due to the demand to quantify and statistically process various plant information from the genetic and cellular level to the individual level. It is also being actively introduced for plant diagnosis and automation in plant breeding, plant factories, and smart farming. A variety of sensors have been developed commercially and for research purposes, ranging from ordinary video and still cameras to spectral image sensors for visible and near-infrared reflections and thermal infrared (temperature) radiation, as well as active measurement systems such as 3D Lidar (laser scanner) and fluorescence. In addition, in order to obtain plant function information, remote sensing from a more flexible platform is required, which can be equipped with the sensors mentioned above. In addition, platforms such as boom lifts (rod-shaped structures like work cranes) and telescopic poles are used. In particular, battery-powered small drones called multicopters with a payload of up to several kilograms and a flight time of several tens of minutes are relatively inexpensive and becoming popular recently. In addition, as the amount of data becomes enormous (big data), data assimilation with models and integration with existing geospatial information is necessary, and also cloud computing has become important.

Figure 2 shows an example of rice quality diagnosis using visible and near-infrared images measured by a modified single-lens reflex (SLR) camera[12]. It is known that the eating quality and yield of rice depend on the leaf nitrogen content at the ear fertilization stage, and in particular, the leaf nitrogen content has a high correlation with the brown rice protein content (Figure 2b). However, the leaf blade nitrogen level is also related to yield, so optimal leaf blade nitrogen level management is needed. The amount of nitrogen in the leaf blade is related to the chlorophyll content. The chlorophyll content of the leaf blade, i.e., the leaf blade nitrogen content, is estimated from visible and near-infrared images at the ear fertilization stage, and the spatial distribution of the brown rice protein content in the paddy field is estimated as shown in Figure 2c. An attempt is being made to use this information for ear fertilization management to optimize eating quality and yield.

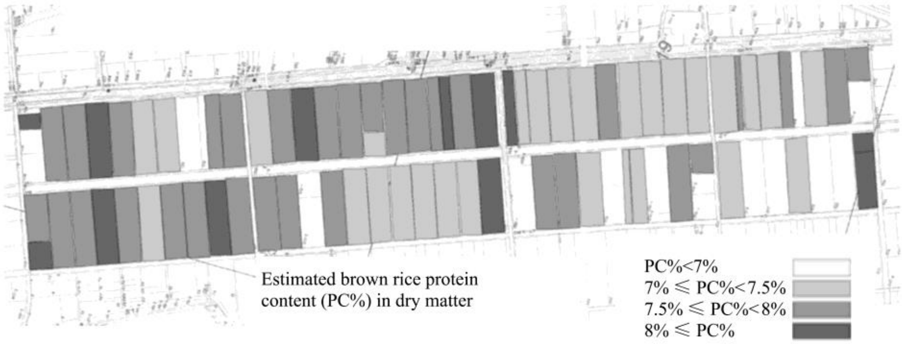
Figure 3 shows an example of 3D measurement of rice plant growth in a paddy field using a drone[16,17]. Using SfM or, Structure from Motion, a passive method that estimates the position and orientation of the camera and the 3D shape of the object from images taken from multiple viewpoints, 3D analysis of the community structure was conducted. Plant height, leaf area index, biomass, and yield can be estimated using the information and used for growth diagnosis. It is also useful for making a 3D map of farmland for automated work.

Figure 4 shows an example of 3D community structure of tomato plants using a ground Lidar (an active method)[13]. It is possible to obtain accurate 3D time-series information of plant functions like changes in growth, structure, leaf area density (LAD), etc., which can be used for cultivation management and growth diagnosis.

a. A photograph of the paddy field

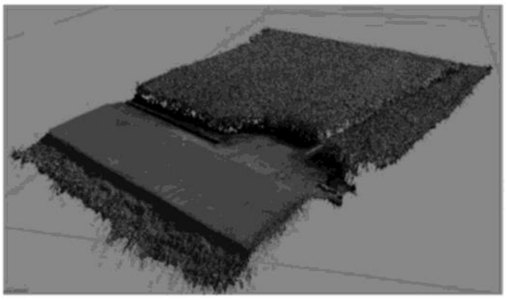


b. Relationship between leaf blade nitrogen and brown rice protein contents

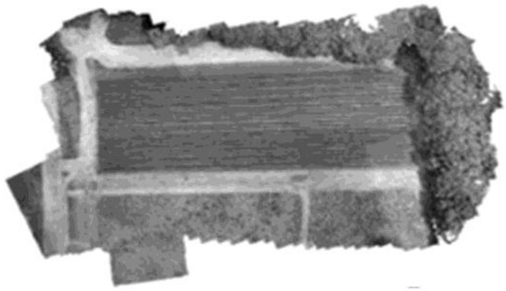


c. Estimated brown rice protein calculated from visible and near-infrared images

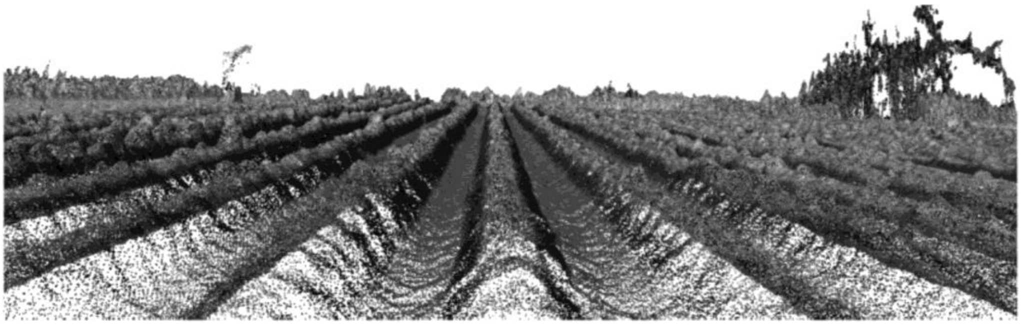
Figure 2 An example of rice quality diagnosis using visible (RGB) and near-infrared images measured by a modified SLR camera[12]



a. 3D image of a paddy field



b. 3D image of sweet potato farmland



c. 3D image of sweet potato farmland[16,17]

Figure 3 Examples of 3D measurement of rice plants in paddy field and sweet potato farmland using a drone
(The images taken by a color camera were analyzed by SfM)

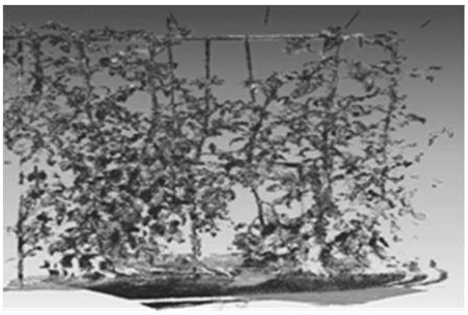


Figure 4 3D tomato community structure using ground Lidar[13]

Chlorophyll fluorescence imaging, a non-destructive and non-invasive method has been used for assessing photosynthesis, which is a key component of biological functions of plants. 3D chlorophyll fluorescence imaging, which contains more information on plant photosynthesis has been developed. Figure 5 shows non-visible photosynthetic effects of herbicide including DCMU on a whole melon (*Cucumis melo* L.) plant was represented using 3D chlorophyll a fluorescence imaging. The image was taken 5 h after DCMU treatment into pot soil[10]. Changes along the leaf veins are evident. A 3D model was constructed by combining the 2D chlorophyll fluorescence intensity images and Lidar-derived 3D model.

Figure 5 An example of 3D chlorophyll fluorescence imaging

Non-visible photosynthetic effects of herbicide including DCMU on a whole melon (*Cucumis melo* L.) plant was represented using 3D chlorophyll a fluorescence imaging. The image was taken 5 h after DCMU treatment into pot soil[10]

3 Development of field smart farm and smart greenhouse

Japan has been facing food security issues. For example, the farming population of Japan has been declining. Therefore, there is an urgent need for developing advance cultivation systems. One obvious solution is the development of smart farming and subsequently, the development of smart greenhouse is another logical solution.

A smart farm developed at Takasaki University of Health and Welfare consists of paddy and vegetable fields and a smart greenhouse. The fields and greenhouses are monitored by network cameras and weather stations, continuously through the in-campus LAN. In addition, color, thermal, multi and hyper spectral cameras, Lidars and chlorophyll fluorescence imaging systems, which are mounted on drones and vehicles, or on ground and in greenhouse, are used to monitor plant functioning and structures (Figures 6-15).

The smart greenhouse is an advanced facility equipped with various environmental control devices and monitor the cultivation environment. It is a gutter connected greenhouse with five bays. Each bay has 9 m wide and 21 m in length. It has eaves height of 4 m, and ridge height of 6.2 m. Bays were connected with attached head house. The total area of the greenhouse is 1350 m^2. Each bay is partitioned to allow for individual environmental control. For example, air temperature, humidity, vapor pressure deficit (VPD), CO_2 concentration, solar radiation, wind speed and the direction inside or outside each bay can be monitored via a cloud system. For outside environment, rain sensor is also installed. Based on the monitoring data, the ventilation system, air circulation fans, thermal/shade curtains and fog cooling system are automatically/manually controlled. Heating and CO_2 supply are carried out by kerosene-type hot air blower, hot water boiler and CO_2 generator. Fog systems which utilize evaporation cooling are also installed. A cooling system with heat pumps is installed in one of the bays. Water and nutrients are automatically supplied for crop cultivation according to the growth status of crops. As greenhouse film, fluoropolymer (ETFE) film which has high diffusion function is used. Also, the quality of harvested products is monitored for the optimal control and quality management. Fruit crops, such as tomato and strawberry plants are being cultivated.

A total of thirteen network cameras with pan, tilt and zoom functions (ten cameras for smart greenhouse, two for fields, and one for PC room monitoring) have been installed for the real-time growth diagnosis of crops in a greenhouse, a field plot, and a rice paddy field. The system can be also used for labor-saving of patrol work by remote monitoring. The network cameras are connected to the PC and NAS (Network Attached Storage) via the university LAN, allowing for real-time monitoring and storage of monitoring images. Multiple network cameras were installed in a greenhouse so that the crop growth can be monitored. The combination of this field monitoring system and the high-performance image sensor mounted on the drone enables more advanced crop information analysis and field management.

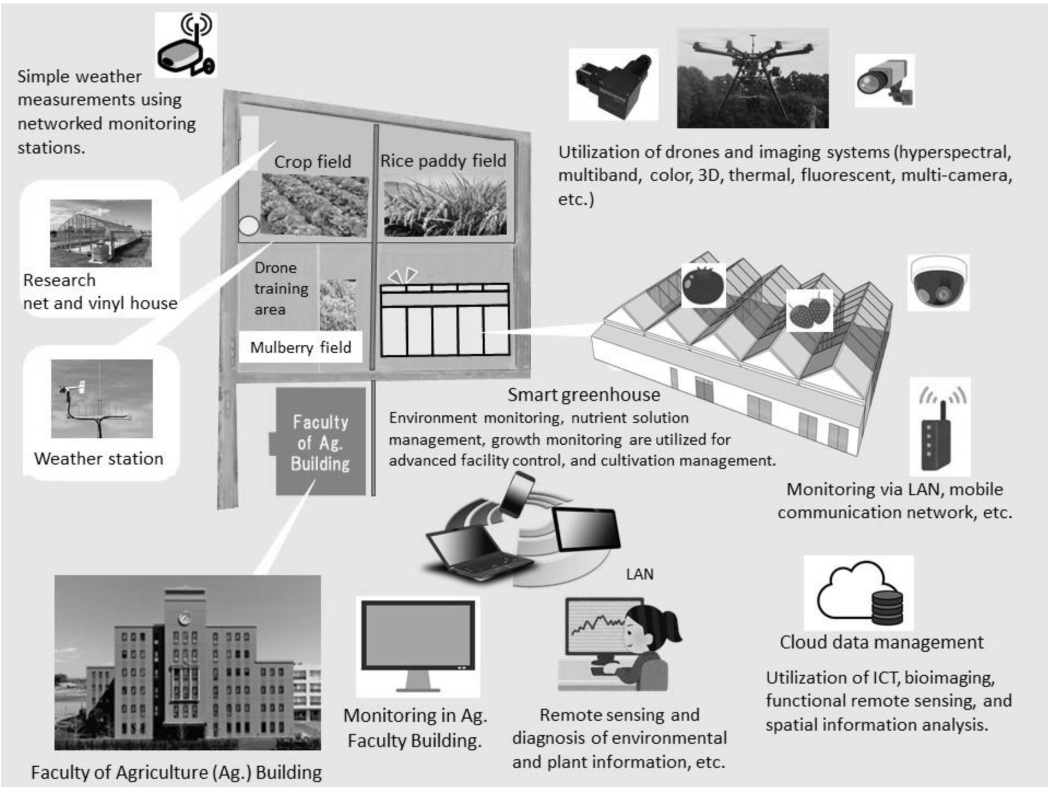


Figure 6 A conceptual figure of the smart farm at Takasaki University of Health and Welfare

Figure 7 A bird's-eye view of the smart greenhouse and paddy field (The Faculty of Agriculture building in the back)

a. A view from the southwest side

b. A view from the south side

Figure 8 Exterior of the smart greenhouse (Each bay has its own sensors)

Figure 9 Three network cameras are strategically installed in a bay for monitoring of the crop growth

Figure 10 Tomato plants were being monitored using a network camera (As greenhouse film, fluoropolymer (ETFE) film which has high diffusion function is used. Greenhouse heating/shading curtains are installed)

Figure 11 Strawberry plants grown on an elevated bench

Figure 12 A 3D textured model of strawberry plants grown on elevated benches in a smart greenhouse (The 3D model was reconstructed from a video captured with a small drone)

Figure 13 A weather station in the field smart farm (A data logger is connected with PC via LAN)

Weather data is important information for crop cultivation. For this reason, a weather station was introduced at the northwestern end of the field (Figure 13), where it is less affected by buildings and the smart greenhouse. The measurement items include air temperature, humidity, total solar radiation, wind direction and speed, rainfall, and atmospheric pressure. All instruments are traceable. The data from the data loggers attached to the weather station can be always monitored via the campus LAN using dedicated communication software on the computer (PC) in the smart greenhouse or in the faculty of agriculture building. The information is stored as a database and can be used for education and research purposes.

Figure 14 Drone remote sensing at the field smart farm of Takasaki University of Health and Welfare

Figure 15 A 3D textured model of the field smart farm (The 3D model was reconstructed from a video captured with a drone. Eggplants are planted on the left and maize plants on the right)

4 Utilizations for plant phenotyping

The production of useful plants is an important issue for solving food, health, environmental, and energy problems. Image information has been conventionally used for gene screening and analysis. Many useful plant traits are determined by the combination of the effects of multiple genes. In addition, morphological and physiological characteristics change in a complex manner depending on the growth stage and environment. Therefore, in plant phenomics, which phenotypes are studied from both genotypic and environmental perspectives, it is important to develop phenotyping technology to obtain information on traits without disrupting the environment while the plant is growing. For practical applications such as plant breeding, it is necessary to analyze the quantitative trait locus, or QTL, that determine the quantitative characteristics. For this purpose, it is essential to have a technology to obtain information on morphological and physiological characteristics in a large amount, rapidly and automatically under the growth environment, and there are high expectations for remote sensing of plant functions.

5 Conclusions

This paper introduced the outline of remote sensing of plant functioning and examples of analysis of 3D structures by remote sensing of plant functions from relatively short distances using drones and ground Lidar. The quality control of rice in the paddy field and chlorophyll fluorescence imaging for photosynthetic diagnosis were also introduced. A field smart farm and a smart greenhouse which heavily utilizes ICT have been built at Takasaki University of Health and Welfare in Gunma, Japan, was also introduced. Multidisciplinary researches are being carried out and systemic effectiveness of the smart greenhouse are being examined using the facility. It is expected that remote sensing technology for obtaining information on plant functions will be developed in the future and its use in smart farming will be promoted.

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