Moonshot R&D MILLENNIA* Program

*Multifaceted investigation challenge for new normal initiatives program

"Green Revolution 2.0"

Initiative Report

9, July, 2021

Goal Investigation Team: SACMOTs

Team Leader: Yūshi Ishibashi (Associate Professor, Faculty of Agriculture, Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University)

Sub-leader: Daichi Tajima

Team Members: Shinya Murakami (Mitsubishi Corporation)

Noboyuki Ario (Sojitz Kyushu Corporation)

Taichi Moriyama (ITOCHU Corporation)

Koichirō Tanamachi (Tanamachi Nōen)

Suriyasak Chetphilin (Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University)

Kyōhei Kai (Fukuoka Futaba Senior High School)

Contents

I. Concept

1. Proposed MS Goal

1.1 Proposed MS Goal Title

"By the year 2050, we will create a Green Valley in Japan, establish agricultural production technology that enables anyone, anytime, anywhere to grow anything, and help realize a world in which everyone may enjoy a rich diet and a life of well-being."

1.2 Vision for 2050 Society

① Amidst drastic changes in the global environment, we will be able to produce and supply enough food for the growing world population.

(1) Create a Green Valley in Japan that will gather human resources, goods, and funds related to food and agriculture from all over the world, establish a next-generation agricultural model, and build innovative production technologies.

→It will be possible to cultivate plants under all types of environmental conditions, with all kinds of crops, and with a new technological system that minimizes environmental impact.

(2) Based on the technology in (1), countries around the world will formulate stable food policies and build well-developed social security systems.

- The technology described in (1) above will expand the means of procurement, including the possibility of complete food self-sufficiency for each country. This will free such countries from food procurement policies that depend on outsourcing from other countries, thereby enabling them to realize stable food procurement even in emergencies, such as the recent spread of COVID-19.
- Each country will promote the development of policies that will procure plenty of food as well as the examination of systems for providing at least the minimum amount of food necessary for the people under certain conditions, which will resemble a basic income scheme, but will instead be a "basic food scheme."

→Realize a world in which everyone may procure nutritious food.

② Help realize a world in which everyone may live their lives in peace and pursue self-fulfillment. (Realization of a society that values well-being in which men and women of all ages can live in their own way and take on their own challenges).

- In Japan, since labor is, among other things, a primary means of securing one's food, the phrase "labor nearly equals food" reflects this essential relationship. However, by 2050, the condition of working for food will no longer be a concern due to the technological development and policies mentioned above.

→Establishing a world in which everyone can pursue whatever they want to do.

③ Solving many other social problems from an agricultural perspective.

Agricultural products are not simply used for food, but also contain the following possibilities.

1. Consider agricultural products as a “place for chemical synthesis” where materials previously made synthetically (raw materials for pharmaceuticals, Chinese herbal medicine, textiles, plastics, etc.) may instead be manufactured efficiently from plants.
2. Extracting energy (electricity) from the plant cultivation process.
3. Other, secondary functions of agriculture will include regional revitalization, disaster risk reduction, and creation of renewable energy sources.
4. Making the above possible “anytime, anywhere, by anyone” in the sky, at sea, or in space.

Fig. Conceptual diagram of the social vision by Team SACMOTs

2. Targets (What achievement of MS Goals could look like in 2050 [and 2030])

① By 2050, we will establish a food production system that will solve food shortages and nutritional deficiencies around the world by fully utilizing cultivation information and innovative cultivation methods that are revolutionary compared to conventional methods.

(1) Dramatic advances in the analysis of plants’ internal information and information on the cultivation environment will lead to the discovery of new plant physiological mechanisms.

➢ Regarding plants’ internal information, miniaturization of sensors is progressing, supported by advances in semiconductor technology. By 2030, it will be possible to introduce single-function sensors (thermo meter, hygrometer, and so on) into plants. By 2050, molecular sessor (analysis for protein, gene, and so on) will be developed and implemented.

- Regarding information on the cultivation environment, in 2030, a system will be in place that will enable the collection of necessary external environmental information at a relatively low cost, mainly through diagnostic imaging data using drones, the technology for which is currently proliferating rapidly.

(2) Based on (1), a new method of plant cultivation will be established in which higher-level substances will be administered to plants, thereby replacing conventional chemical fertilizers and pesticides.

- By 2030, the efficient use of materials that are currently in development (biofertilizers, biopesticides, biostimulant materials, etc.) will be established. Especially regarding biostimulants, the formation of frameworks for their use has recently begun, and it is expected that they will operationalize under appropriate rules in the near future.
- By 2050, new cultivation methods that high quality materials.

(3) Most cultivation processes will be automated. Plant factories will also become overwhelmingly popular as places to realize the technologies developed in (2) with greater precision.

- In Japan, GPS-equipped machinery is already being developed and put to practical use, especially in rice farming machinery. Companies expect to implement this GPS technology throughout society between 2025 and 2030. In addition, several venture companies in Japan are already working on developing harvesting robots to automate the harvesting process, which is said to consume the majority of farming time. By 2030, it is conceivable that the production of most agricultural products will be automated.
- Regarding plant factories, a profitable cultivation package is currently being established for some leafy vegetables, provided that a certain scale of cultivation and stable sales channels are secured. In 2030, technological innovation will focus on hardware approaches, such as efficient electric irradiation and securing inexpensive energy sources, with some products expected to become more popular than ever.
- By 2050, it will be started to cultivate plants much more efficiently to use auto technology corresponding to new cultivation methods.

② By 2050, based on the food materials that may be stably secured by the technology described in ① above, a new food supply system will be established, including the design of new social security systems, so people around the world will be able to procure enough food to meet their needs.

③ By 2050, encouraging utilizing chemical synthesis based on agricultural products and renewable energy, generating electricity using agricultural products themselves, revitalizing local economies using agricultural land, and conducting disaster risk management.

④ By promoting in parallel ethical, legal, and social implications (ELSI) discussions on the technologies described in ① as needed, we will proliferate their use worldwide by 2050.

3. Background (Reasons for setting these MS Goals, the social significance of achieving them, etc.)

3.1 Why now?

① Demands from society

(1) The necessity of balancing increased food production due to population growth and consideration of environmental impact

In the year 2050, the world population is estimated to increase more than 20% to a total of just under 10 billion people[1]. However, according to a 2020 UNICEF report, as of 2019 we have already had a food shortage problem since approximately 690 million people are starving worldwide[2]. Since the Green Revolution, food production has steadily increased on a global scale[3], the growth of which has been supported by chemical fertilizers and agricultural chemicals. However, the use of these materials is now being reconsidered from the perspective of their environmental impact[4]. In addition, global climate change is expected to exacerbate poor harvests of agricultural products among other problems[5], leading to doubts about whether increasing food production can actually proceed at the same pace moving forward.

(2) Food security issues in the age of COVID-19 and changing attitudes toward food

The novel coronavirus COVID-19 was initially confirmed in China in December 2019, yet it is still raging across the world as of June 2021. In response to the spread of this virus, Russia, Ukraine, and other countries have restricted the export of wheat, corn, and other crops, with confusion in some areas of food distribution as well[6]. However, even before the COVID-19 pandemic, China, with its large population and growing economic power, had become a major player in global food distribution. According to a former employee of a trading company, wheat transport ships that used to go directly to Japan now first go through Singapore and Hong Kong, with Japan increasingly seen as an underdog in price negotiations. Even though Japan still boasts the world's third largest GDP and the world's tenth largest population, it finds itself in this situation. In countries with weaker economies and smaller populations than Japan, the hurdles to securing food in the global distribution system are getting tougher every year.

Additionally, in Japan, the pandemic also inspired a change in consumer awareness of food. More people are cooking at home with greater attention being paid to safe and delicious agricultural products[7]. For example, the number of people purchasing produce directly from farmers has tripled since before the pandemic began[8][9]. Although the number of such direct purchasers is still small compared to the total number of produce consumers, consumer awareness of safe and secure food is certainly increasing.

(3) An era in which people expect to live a life of well-being that is true to humanity

The novel coronavirus COVID-19 has accelerated the automation work previously done by humans. When we think about humanity again, we may take a cue from Maslow's hierarchy of needs. According to his hierarchy of needs, the highest-order need is self-actualization. Various processes lead to self-actualization, but at the core are physiological needs, especially the need for food, which must be satisfied for the continuation of life[10]. In a world where machines are replacing human work, we must tackle initiatives that will contribute to the stable production and supply of food so that people around the world are empowered to aim for self-realization.

(4) Voices of young people, future leaders of the next generation

In a workshop we conducted for senior high school students, we interviewed them about their image of an ideal society in 2050. One result of the workshop was that, after discussing their concerns about food production challenges in Japan, 97% of the students answered that an ideal self-sufficiency rate would be 60% or more. Additionally, 70% of the students answered that they are not resistant to genome editing. This shows that establishing new food production technology that fully utilizes science and technology and securing stable food procurement routes are in high demand by the generation of students responsible for the future.

(5) Worsening of global warming

Efforts toward reducing reliance on oil and fossil fuels are rapidly progressing. In Japan, introducing charges for plastic bags as a general rule has likely triggered a strong awareness of the importance of reducing waste among general consumers. Last year, Prime Minister Yoshihide Suga declared that he would aim for carbon neutrality (virtually zero greenhouse gas emissions) by the year 2050, leading to a range of industries accelerating their efforts to move toward a decarbonized society[11].

② Demands for science and technology

(1) Japan's world-class agricultural data and know-how

Looking at company rankings in terms of market capitalization and the number of patent applications, Japan is losing its international standing. In particular, the presence of IT companies such as the so-called GAFAM companies from the U.S. and the BATH companies from China, which are dominating the world as of 2021, is very significant[12)13)]. Under these circumstances, what kind of technology and know-how does Japan still have ahead of the rest? According to some agrochemical manufacturers, Japan possesses more than 50% of the world's bulk agrochemicals that have not yet been put on the market, and its knowledge of plant physiological mechanisms is said to be among the best in the world. Japan has the potential to lead the world in technology and know-how related to plants and agriculture in the future.

(2) The inclusion of many issues that need to be addressed as a mid- to long-term R&D program in Japan

Since research and development in the field of agriculture requires the actual cultivation of plants, which is inescapably accompanied by weather risks, etc., mid- to long-term efforts are essential. In addition, although we refrain from describing the details in this report, the following technological developments that are not directly related to agriculture are also essential for revitalizing domestic agricultural production, many of which should be addressed as part of Japan's R&D programs.

- ✓ Establishment of a low-cost renewable energy supply system
- ✓ Improved accuracy of GPS, image analysis, etc.
- ✓ Miniaturization and improved longevity of batteries
- ✓ Faster transmission speeds

3.2 Social Significance

① Satisfying the food needs of people worldwide, supporting health infrastructure, and simultaneously caring for the global environment

As mentioned in section 3.1, it is possible to produce sufficient amounts of food to meet the needs of a growing global population while minimizing the burden on the global environment. Conventional agriculture is based on the mass use of chemical fertilizers and pesticides. Research has determined these materials to be a cause of greenhouse gas emissions, water and soil pollution, and have had a tremendously negative impact on the global environment. With new technology, however, use of chemical fertilizers and pesticides can be drastically reduced, yield-per-unit area can be drastically increased without increasing the area of cultivation (no need to cut down forests, etc.), and food production may be increased.

(Targeted SDGs)

SDG 1: No poverty

SDG 2: Zero hunger

SDG 3: Good health and well-being

SDG 9: Industry, innovation, and infrastructure

SDG 12: Responsible consumption and production

SDG 13: Climate action
SDG 15: Life on land
SDG 17: Partnership for the goals

② Improving the happiness of humanity

(1) Japan boasts the world's third largest GDP, but according to the World Happiness Report published by the United Nations every year, Japan ranks 56th in terms of happiness[14]. Though happiness rankings correlate to a range of factors, one that highly correlates to happiness is the food self-sufficiency rate (because a low food self-sufficiency rate makes it difficult to achieve high-capacity-high-benefit welfare systems). Many of the top-ranking Nordic countries have achieved a food self-sufficiency rating of 50% or higher, meaning not even top-ranking countries enjoy a 100% food self-sufficiency rate[15][16]. Further developing this technology will improve self-sufficiency in Japan and other food-importing countries, and partially correct the inequality among nations.

(2) As mentioned in section 3.1, with the development of AI, IoT, etc., more and more jobs will be replaced by machines and robots in the future. In such a world, the pursuit of self-fulfillment will become very important for people to feel human. Establishment of stable food production and supply systems will be the foundation and play a very important role for people's pursuit of self-fulfillment.

(Targeted SDGs)
SDG 8: Decent work and economic growth
SDG 9: Industry, innovation and infrastructure
SDG 10: Reduced inequalities
SDG 16: Peace, justice and strong institutions

③ Drive technological innovation in other industries and solutions to important issues other than "food"

(1) Currently, most agriculture is conducted in regional communities rather than in urban areas. Therefore, revitalizing agriculture will directly lead to the revitalization of non-urban regions (by providing jobs for the elderly who live in the region in high proportion and resolving the problem of increasingly abandoned, unutilized land). In particular, resolving regenerating otherwise wasted land will, in the end, contribute to countermeasures against disasters.

(2) Agricultural products are now attracting a lot of attention as raw materials for energy production. Bioethanol fuel in particular is becoming popular in Brazil and other Western countries. When we achieve this goal, we will be able to control the composition of nutrients in plant bodies, which will make it possible to obtain biofuel more efficiently than we can

currently. It is also possible that a new power generation model will be developed by focusing on the metabolic mechanisms of plants themselves.

(3) Much recent research focuses on improving bioplastics and reducing the use of plastic bags, all toward the goal of reducing reliance on petrochemicals[17]. Once plants are viewed as a viable site for chemical synthesis, it will be possible to maximize plants' potential and synthesize all kinds of things inside of them.

(Targeted SDGs)
SDG 7: Affordable and clean energy
SDG 9: Industry, innovation and infrastructure
SDG 11: Sustainable cities and communities
SDG 12: Responsible consumption and production
SDG 17: Partnerships for the goals

④ Improving Japan's international position

As mentioned in section 3.1, Japan's international status is on the decline, but in the field of agriculture, Japan is currently in a leading position globally. In terms of the near future as well, Japan has an overwhelming advantage in research and development regarding agriculture because of the country's long north-south axis, four seasons, and wide variety of environmental conditions that allow for the cultivation and research of a relatively large number of plant species.

3.3 Action Outline

① Industries:

(1) Agricultural firms and large-scale farmers: Necessary initiatives include actively adopting the technologies developed by Green Valley, utilizing more efficient cultivation methods, and striving to create a strong industry of their own to produce higher-quality agricultural products.

(2) Agro-material manufacturers: Aggressive research and development of each technology is desirable from the following perspectives.

- Development of UI/UX and its cost as imagined for use in agricultural fields
- Development of materials that minimize environmental impact
- Actively convert more advanced technologies used in other industries for use in agriculture

(3) Companies that have contact with "food" (e.g., food products, retail, and restaurants): We hope these entities will actively participate (invest) in the agricultural sector from the viewpoint of traceability and stable procurement more than ever before.

② Universities and research institutes:

(1) Foundational technology development: In collaboration with agricultural material manufacturers, we would like to promote foundational research on plant physiology with an exit plan.

(2) Education: More and more artificial methods will be added to the field of agricultural production in the future. For example, universities and research institutes will need to disseminate sufficient information so that we do not repeat the history of genetic modification technology, which was not accepted by consumers and did not proceed smoothly in research and development.

③ Administrations and municipalities:

(1) Legislation, information organization and dissemination: After organizing and disseminating pertinent information in cooperation with universities and research institutes, and inspiring an appropriate public opinion, it is necessary to formulate a framework for practical use, including legislation, so that the technology developed by Green Valley can be implemented smoothly.

(2) Construction of a social security system: Early on when the technology developed by Green Valley has been implemented, we would like to study how to create a well-developed social security system based on stable and sufficient food supply.

(3) Other inter-industry and inter-country adjustments:

- Green Valley will create a framework, including taxation controls, to ensure that not only existing agricultural industries, but other industries as well enter the new ecosystem.
- Resulting from technological developments by Green Valley, it is possible that the import and export position of each country's agricultural products will change significantly. If that turns out to be the case, adjustments will be made to avoid excessive trade friction.

4. Benefits for Industry and Society

① Changes in agricultural production:

Innovations will occur in the way agricultural production is carried out around the world. In each country and region, the technologies to be introduced will vary depending on the external environment and the crops to be grown, but in general, the following changes will progress presuming the introduction of advanced sensing technologies.

(1) Increasing scale and remote control to accompany automation.

(2) Using substances with low environmental impact to replace conventional chemical fertilizers and pesticides.

② Food distribution and procurement:

(1) The suitable areas for cultivation of each crop differ from those that were suitable with conventional agriculture, which may lead to changes in the food procurement strategy, trade strategy, and ultimately the position of each country.
(2) Countries will be able to start considering more generous social security policies based on stable food procurement. Some countries may even consider a "basic food" system that guarantees a minimum food supply for daily life. In any case, countries around the world will be able to guarantee a stable food supply for their citizens. This will ultimately lead to empowering people the world over to pursue a more fulfilling life for themselves. In turn, this will lead to increased happiness.

③ Impact on other industries, etc.:
(1) Technology from Green Valley will become a new export industry for Japan and contribute to raising Japan's GDP.
(2) Starting with agriculture, regional economies and efficient use of renewable energy will improve.
(3) Many of the chemical products derived from fossil fuels will be replaced by plant-based products. The petrochemical industry, which drove economic growth in the past, will be replaced by the plant-based industry, which will take over manufacturing for the next generation and drive economic growth.
(4) As agricultural entities become larger in scale, the profitability of agricultural producers will improve overwhelmingly. This will lead to the emergence of relationships between agricultural producers and retailers, the restaurant industry, and wholesalers. In turn, these changes will contribute to improving the food industry as a whole by optimizing inventory (i.e., reducing food loss) and strengthening traceability.

II. Analysis (Statistics and Bird's-Eye View)

1. Essential scientific/social components
(Issues [scientific/social] and actions necessary to achieve MS Goals)
① Scientific Issues:
(1) Developing advanced sensor technology
Moving forward from item (2), sensor technology will be at the core of all technological development. In the development of machinery as well as new materials, it will be essential to improve the accuracy of data-sensing technology for plant internals and the environment in which they will be cultivated.
(2) Developing algorithms to optimize the balance between plant and cultivation environments
In conjunction with item (1), it is necessary to develop a method to quantitatively evaluate

the interaction between the environment and arable land management by integrating soil, crop, and community micrometeorological models, and to develop algorithms for the most efficient cultivation of each crop under each cultivation condition.

(3) Developing new plant breeds

After the rediscovery of Mendel's law, scientists developed the foundation of current breeding technology between 1910 to 1920, after which genetic recombination and genome editing technologies were introduced[18)]. This direct scientific approach to plant cultivation has attracted the most attention.

(4) Developing cultivation techniques that do not rely on chemical fertilizers and pesticides and that minimize environmental impact

Recently, biofertilizers/pesticides, biostimulant materials, and the development of RNAi technology to improve photosynthetic efficiency are attracting attention as next-generation fertilizers and pesticides[19)]. Additionally, in terms of spraying methods, pinpoint spraying by drones using the above sensing technology is also attracting researchers' attention.

(5) Developing automation technology

No matter how advanced various technologies become, it is essential to increase the income of agricultural producers in order to enable them to adopt new technologies proactively. On the other hand, it will be difficult to achieve this MS goal unless the final products (agricultural products) are available for a relatively low cost. In order to achieve low costs, it is essential to realize near-full automation and to dramatically increase productivity (cost reduction).

(6) Plant factories

In order to utilize the above technology with maximum efficiency, it is necessary to minimize the influence of the external environment, with development of next-generation, completely closed plant factories desirable.

② Social Issues:

(1)Challenges for disseminating the science and technology described in section ①

(ⅰ) Expanding the scale of agricultural production, digitalization of various processes

It is basically necessary for agricultural producers themselves to invest in the introduction of each technology. To do so, it is necessary to expand the scale of production, maximize the use of new technologies, and create an environment that will ensure the profitability of these investments. In Japan, for example, the following measures will be necessary.

- Ministry of Agriculture, Forestry and Fisheries (MAFF), JA Group, and local municipalities: Promote information and legislation to enable farmers to expand their farmland.
- Food manufacturers, restaurant industry, etc.: The challenges that agricultural producers face when expanding their scale of operations are securing human resources and sales

channels. We hope that food manufacturers, restaurants, and other large companies that use agricultural products will actively collaborate with agricultural producers to resolve stability issues. One specific example would be major manufacturers dispatching human resources to agricultural production sites and increasing opportunities for direct purchase of agricultural products from producers.

- Agricultural producers: Many farmers are engaged in agricultural production as an extension of their subsistence lifestyle, or who are not particularly interested in new approaches and are just following the same procedures as always out of habit. However, as the number of farmers is expected to decrease drastically in the near future, it is necessary for them to expand the scale of their operations and pursue greater efficiency without being bound by conventional thinking.

(ⅱ) Deregulation and promotion of agriculture-related technologies:

Deregulation and reduction of psychological hurdles for consumers to new science and technologies are essential so that the accelerating progress of science and technology can be smoothly implemented in society.

(ⅲ) Establishment of an integrated research system from basic to practical use

It is desirable to promote collaboration between various fields of agronomy (crop science, ecology, soil and fertilizer science, agro-meteorology, etc.), materials development, and agricultural production, where crop productivity and material cycles in actual production sites are the targets of research.

(ⅳ) Human resource development

There is an overwhelming shortage of physiological ecologists and agronomists who understand “material cycles in the field” and the physiological ecology of the plants that carry out these materials cycles from a field-scale macro perspective. In university biology and agronomy departments, many students apply for molecular biology and plant physiology majors, but not many apply for research specializations related to field surveys and measurements, such as ecology, crop science, and agro-meteorology. In order to promote the development of human resources in the future, it is necessary to actively promote the importance and attractiveness of these fields both domestically and internationally, and to strengthen exchanges with fields related to global warming and climate change countermeasures, which are of high social interest, in addition to collaborations with fields such as molecular biology and plant physiology.

③ International collaboration, cross-disciplinary and cross-sectoral collaboration, and efforts regarding ELSI, etc.:

(1) Cooperation in science and technology: As mentioned above, Japan has a long area of land from north to south and a wide variety of cultivation approaches, so it is possible to establish

many cultivation models, but it is impossible to establish a single model for all plant species and all cultivation patterns in Japan alone. When working to improve food self-sufficiency in each country, it is necessary to localize these models through collaboration with appropriate organizations. Smart agriculture-related technologies also already exist in many countries around the world, so rather than exporting services in terms of language and customs, it is necessary to localize approaches developed in Japan, for example, by proactively incorporating extant local technologies and approaches.

(2) Improving consumer sentiment when introducing new technology to the food and agriculture industry: As in Japan, it is important to control consumer sentiment. Since this issue is closely related to cultural and religious backgrounds, it is essential for each country to be fully involved in the process.

(3) Integration with industries other than food and agriculture: Some efforts have already been made to use agricultural products other than for food-related purposes, such as the industrial use of cornstarch and bioethanol, but in the future, it will be necessary to set up opportunities to promote integration with a wider range of fields (medicine, various materials, etc.).

(4) Adjustment for trade friction and tariff issues: As mentioned above, if the food procurement strategies of each country change, the current trade balance will be upset, which could cause major problems. However, this change should be viewed as a return to the way things should be. We hope that countries will cooperate and coordinate with each other in an understanding manner.

2. Science and technology map

(Overview of research and development to be conducted to achieve MS Goals)

① Developing advanced sensor technology

Sensor technology is the gateway to so-called “smart agriculture.” Physical sensor technology is already improving dramatically, including data analysis on plant cultivation environments, such as temperature and humidity, and analysis of plant conditions from the outside through images. However, the following issues remain to be solved before these technologies can be put to practical use in full-scale agriculture.

(1) Improving practicality (lower power consumption, ensuring robustness and stability, and improving accuracy): Even if no problem exists with laboratory use, when considering use in the field, the problem is that power consumption is large, robustness cannot be sufficiently ensured, and, depending on the device, safety cannot be guaranteed. Additionally, in order to ensure accuracy, calibration and surface cleaning are necessary before use, but such precautions are usually not possible or are too costly.

(2) Improving communication infrastructure: Ideally, images and video information would be

sent to the administrator in real time, but the communication environment to make this possible has not yet been developed. The development of high-speed, large-capacity, low-latency communication infrastructure, so-called “5G” and beyond, is required.
(3) Innovating drone technology: The use of drones is making it possible to acquire fixed data as well as data acquired while moving around the cultivation area. However, drones consume batteries quickly and require spare batteries for use in large farms, not to mention the manpower needed to replace the batteries.
(4) Establishing new sensing methods: Currently, technologies are being developed for sensing the external environment and the surface of plants, but the data obtained from these methods is, so far, very limited in terms of improving our understanding of the cultivation status of plants. With an eye toward 2050, development and practical application of molecular sensors (which attaches detected molecules and recognition molecules that specifically interact with other substances [e.g., nucleic acids, peptides, proteins, low-molecular-weight compounds] to electrochemical devices [transistors] and the transducers of optical devices so that it may detect changes in electrical or optical signals caused by the interaction between the detected molecules and the recognition molecules that interact with other substances) is proceeding in earnest[20). Such sensors will help us acquire more detailed data regarding plant internals and improve our ability to more quickly understand the status of the plant’s body and prescribe the appropriate substance at the most appropriate place and at the most appropriate time. The tasks necessary for achieving this capability are essentially the same as those for the physical sensors described above.

② Developing algorithms to optimize the balance between plant body and field environments
Algorithms to optimize the balance between plant body and field environments began to take off in the 1960s. In the 1980s, simulation models of crop production and soil nutrient water dynamics were developed, and in the 1990s, biogeochemical models were developed to predict crop production and the release of trace gases, including greenhouse gases, from soils. Biogeochemical models have since been used to estimate greenhouse gas emissions over a wider area than field-level predictions[21)]. The scientific and technological challenge in algorithm development is the development of quantum computers that can handle large scale complex data, primarily omics and phenotyping data. However, the most limiting factor in this development is the research infrastructure, including the lack of fields where experiments can be conducted with multiple environmental control systems and the lack of collaboration between phenotyping analysts and algorithm developers.

③ Developing new plant breeds
In the past, it would typically take 10 to 15 years to produce a new plant variety. However,

DNA marker breeding, genetic recombination, and genome editing technology using CRISPR/Cas9 (which was announced in 2012) have dramatically shortened the time it takes to breed new plants. The most important feature of genome editing technology is that, by utilizing the CRISPR/Cas9 and other nucleases, the accuracy of the DNA targeting is very precise and crop breeding with the targeted traits and functions can be achieved much more accurately and in a shorter period of time[22)]. However, the scientific and technological issues are as follows.

(1) Reliable and drastic modification of breed characteristics

Only a limited number of genes can be edited at one time, and the effect this editing has on plants is similarly miniscule. In addition, neither do we fully understand the functions of plant genes, nor do we understand which genes may be changed for desirable outcomes.

(2) Technology to develop completely new plant breeds

Genetic modification and genome editing technologies have not been fully understood by the general public due to researchers' lacklustre success over the years. In the future, it may be necessary to replace these technologies with new breeding methods that do not modify the genome itself and, as much as possible, do not rely on artificial methods.

④ Developing cultivation techniques that do not rely on chemical fertilizers and pesticides and that minimize environmental impact

After the successful establishment of the Haber-Bosch process for ammonia production in 1909, the use of chemical fertilizers became more widespread. Moreover, the Green Revolution led to the creation of varieties with high fertilizer responsiveness, which encouraged the further use of such fertilizers. Chemical pesticides also became widespread in the 1900s, becoming even more prevalent during the post-WWII food shortages[23)]. However, chemical fertilizers use a large amount of fossil fuels in their manufacturing process, their excessive use is feared to cause water, soil, and air pollution, and researchers have proven that the use of chemical pesticides also causes ecological destruction[24)]. The development of materials to replace these problematic tools is as follows.

(1) Pursuing efficient use of biofertilizers/pesticides and biostimulants: The effects of these materials are not yet clear, and the speed of their adoption is slow. Some believe that these materials are inappropriate as substitutes for existing pesticides, but it is highly likely that they will be used in combination with existing pesticides. Regardless, how to more efficiently use these newer, less harmful substances is a research priority.

(2) Reducing the amount of chemical fertilizer and pesticide inputs (improving efficiency): Technological development for reducing the amount of chemical pesticides to be sprayed includes partial spraying combined with image diagnosis by drones. However, in addition to the battery problem mentioned earlier, drones have limited cargo weight. As a result, it is not

possible to load a sufficient amount of materials for efficient fertilizer and pesticide spraying. Toward 2050, it may be possible to establish a completely new cultivation method using method of introducing materials that has already been widely used in the medical field.

⑤ Developing automation technology

The mechanization of agricultural work, such as through use of tractors and combine harvesters, has been progressing for a long time. Now, with the support of new basic technologies such as GPS and image analysis, robots and machines may be able to handle an increasingly wide range of work processes, including sowing, weeding, and harvesting. The challenge is how to make them more practical. Specifically, the key points are as follows.

- Even if a machine is specialized for a specific task and is intended to be fully automated, it cannot perform the peripheral tasks that still require human labor (e.g., a harvesting robot can automate harvesting, but loading and unloading baskets is done manually).
- Uneven work due to insufficient accuracy of various sensor functions
- The number of batteries is insufficient, and even if the machines are designed to be unmanned, the reality is that they still require human labor. As a result of these problems, the number of human workers cannot be sufficiently reduced (to zero), and because of this, the cost effectiveness remains unsatisfactory.
- Ensuring robustness and stability
- Establishment of various data collaboration systems

⑥ Plant factories

By 2005, cultivation methods had already been established for crops with short growing periods, such as lettuce and herbs. In 2009, the Ministry of Agriculture, Forestry and Fisheries (MAFF) and the Ministry of Economy, Trade and Industry (METI) launched a nationwide project to develop bases for plant factories, setting in motion the so-called third boom in plant factory construction. The goal was to triple the number of plant factories and reduce production costs by 30% while also expanding sales channels and reviewing cultivation systems to optimize and save energy. In addition, efforts were made to change the light source for cultivation from fluorescent lamps to LED lighting. By 2016, the number of plant factories had increased to 191 (compared to 50 in 2009). Furthermore, the expansion of sales channels and progress in energy conservation have made it possible to realize mass-produced plant factories containing more than 5,000 plants each day. However, due to the fundamental issue of high cost structures in production, more than half of the plant factories are doing poorly financially[25]. Since around 2014, plant factories are being built on a larger scale in order to reduce costs. The challenges are as follows.

(1) Improving sensor technology: The accuracy of quantification typically needs to be on the

order of several percent, which is one order of magnitude higher than conventional physiology.

(2) Greater sophistication of algorithms:

- Many algorithms are inadequately applied to spatio-temporal scales (tens of centimeters to several meters, with a growing period of weeks to months) that are different from the model plant (Arabidopsis thaliana).
- A plant factory is a system that uses sequence control to optimize the growth environment for plants. It's important functions are controlling the order and timing of various environmental inputs given to the plants and determining the optimal environmental input pattern (algorithm) from among a vast number of combinations.
- Currently, algorithms are being considered only for certain items, such as leafy vegetables, but we would like to expand it horizontally in the future[26)27)28)].

(3) Interaction with other new technologies: Interaction between the latest engineering technologies, such as automation of cultivation and production processes using work equipment/robots, and crop breeding, such as cultivation tests and production of genome edited crops.

(4) Maintaining a steady state in the production process: The amount of light received by the plants, the composition of the nutrient solution, and the composition of atmospheric gas are difficult to keep constant due to the interaction between plant growth, physiological metabolism, and the aging (deterioration) of the equipment.

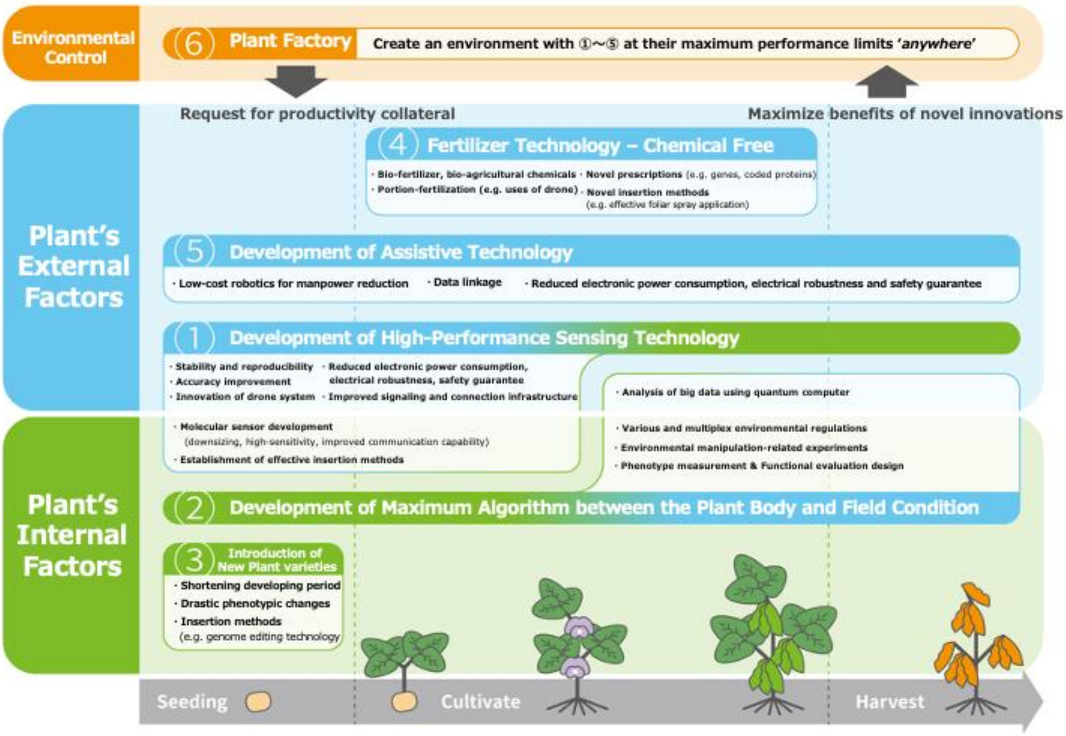

Fig. Overhead view of research and development to be conducted to achieve MS goals

3. Japan’s position in overseas trends

(Trends in R&D related to the targets [overall], overseas trends, and Japan's strengths)

Currently, the focus of research and development at the commercial level in the agricultural sector is on four major foreign companies—Corteva Agriscience, Bayer, Syngenta, and BASF—which have pursued large-scale M&A and business integration. Gross sales of their seeds account for 60% of the total market, with sales of other materials also substantial. In agriculture, differing government-led policies mean the market environment is inconsistent, but these Big Four companies have established local subsidiaries in each country in order to develop businesses that take advantage of their strengths within the scope of regulations in each country and build a solid portfolio[29)]. However, no single company conducts vertically parallel research and development of all the above-mentioned science and technology topics. Since the integration of a wide range of science and technology is essential for this MS goal, there is a limit even for these Big Four companies.

On the other hand, based on R&D trends in each country, no country has been able to efficiently apply the above-mentioned technology to all crop species and cultivation methods. However, some countries are actively conducting research and development on crop species and cultivation methods that are primarily used in their own countries. In this section, we will introduce the case studies of land use crops in the U.S. and China, the case studies of horticulture in the U.S., EU (the Netherlands), and Israel, and finally, the status of R&D in Japan to show its overall research trend and Japan’s strengths. International projects are described in the section for the country where the base is located or where there are many participating teams for the sake of convenience.

① U.S.

(1) Academic level

- U.S. Phytobiomes Alliance: Led by the American Phytopathological Association, this project promotes research on the totality of related, interacting organisms based on plants (crops), with both above- and below-ground parts being analyzed.
- Modeling, physiological analysis, and large-scale FACE experiments are being conducted to predict changes in crop yields due to global warming. Large-scale research to improve photosynthetic efficiency is also being promoted ahead of the rest of the world[30)].
- An international collaborative research group—Realizing Increased Photosynthetic Efficiency: RIPE—which is supported by nine organizations, including the Bill & Melinda Gates Foundation, has announced a series of dramatic improvements in photosynthetic efficiency since 2019[31)].
- In 2019, as part of a project, AgMIP released a large dataset—Global Gridded Crop

Model Intercomparison: GGCMI—that models the growth and yield of 15 different crops with 14 different crop models. This large-scale data set will cover the entire globe in a fine grid, which will allow researchers to simulate the growth and yield of crops in different regions of the world using various crop models provided in the data set along with varying parameters, such as soil nitrogen concentration, meteorological data, and atmospheric CO_2 concentration. It is expected that researchers from all over the world will be able to utilize this dataset and compare the results of crop models from various perspectives, which will enable more accurate yield prediction[32].

- As for sensor technology (nanomaterial technology), the spectrum of research and development is wide due to the abundance of researchers. New ideas often come from the U.S., and basic research motivated by practical application is being conducted mainly at famous universities, such as Stanford University, UCBerkeley/Davis/Irvine, University of Michigan, Georgia Tech, etc.[20]

(2) Commercial level

- The U.S. manages more than 30 positioning satellites at any given time and is the world leader in GPS guidance technology. This technology enables the following in the U.S.[33]
- The accumulation of crop and soil data from satellite imagery is also progressing. FarmLogs is leading the way in this field, raising $22 million to develop its services, which are being used by approximately one-third of U.S. farmers[34].
- GPS-equipped machinery along with sensor technology, especially with regard to large agricultural machinery for large-scale cultivation, is leading the way, with research and development on automation and labor saving advancing in lockstep.
- Drones are also being used to spray pesticides and its market is expected to be worth US$144.8 million by 2025. U.S. drones are characterized by fixed-wing types, which account for about half of the market share. Fixed-wing drones in the U.S. feature long flight ranges (they can fly for more than one hour, about six times longer than the rotary-wing types), large payloads and, due to the abundant availability of runways, fixed-wing drones have become the mainstream. In terms of functionality, the crop spraying segment is the primary focus, with Deere and Company (and other companies) making efforts in this area. Deere and Company acquired Blue River Technology, which specializes in combining AI and agricultural equipment, and is developing a tractor-integrated weeding system using image recognition technology[35], which aims to reduce herbicide use by 90%.
- In the U.S., about 95% of leafy vegetables are produced on the West Coast and delivered throughout the United States, meaning food mileage is a considerable problem. In recent years, abnormal weather conditions have led to the spread of E. coli food poisoning from lettuce, which has contributed to heightening social awareness of food security. Many

companies in the U.S., including start-ups, are developing fully artificially-lit plant factories, with major companies such as Plenty and AeroFarms using their own growth systems, sensors, and AI technology to enable highly efficient production (some crops can be harvested up to 350 times more efficiently than conventional crops[36)]. Traptic has developed a tractor-integrated strawberry harvester using its proprietary vision system and robotic arm technology, which can pinpoint the location of strawberries to within a millimeter, making it possible to harvest delicate fruits and vegetables that have been difficult to mechanize. In the future, the company plans to develop harvesters for a wide variety of vegetables and fruit trees, such as oranges, melons, and peppers[29)].

② China

(1) Academic level

- The Nanjing Institute of Soil Science, Chinese Academy of Sciences has made remarkable achievements in rice-wheat FACE experiments. Research collaboration with Japan is also underway. Government support for chemical ecology and molecular ecology is also substantial.
- The National Academy of Sciences, Nanjing Agricultural University, and other institutions are conducting crop modeling research in field, region, and global cases. In addition, government support for chemical ecology and molecular ecology is substantial.
- Peking University is conducting research on volatile compound sensing using a wide variety of nanomaterials (successfully detecting not only molecules but also viruses and other substances in exhaled air)[20)].

(2) Commercial level

In China, large-scale and highly efficient alley farming is progressing, mainly due to advances in drone technology. The companies DJI and XAG in China are the world leaders in total area sprayed by agricultural drones; the total area of arable land in China where DJI agricultural drones are used reached 34 million hectares in 2020. In particular, DJI has accumulated know-how in RTK+AI technology, which has empowered most drones in China to be controlled by AI without the need for a pilot or controller. (In Japan, due to conflicts with the Civil Aeronautics Act and other regulations, AI control of drones is limited to Level 3.) In 2018, DJI launched a granule spraying system that can automatically handle fertilizer and even sow cereal seeds smaller than 5 mm. The same company is working on a large-scale, high-efficiency cultivation model from sowing to cultivation mainly using drone technology. (The granule spraying system 2.0 released in 2019 is 70 times faster than manual operation.) XAG has also developed an agricultural robot capable of automatic operation based on its core technology of high-precision navigation and has realized automation of weeding, transportation, and patrol, etc. In the future, China is expected to utilize the drone and robotics technologies of both companies to further promote large-scale, labor-saving production of open field products. DJI and XAG were founded in 2006 and 2007, respectively, with both companies building up their technology and releasing the world's first automatic drone in 2016 with particularly accurate automatic flights compared to others around the world. Recently, flight lengths and camera sensitivities have been increasing (the T20, released in 2019, had a flight time of 15 minutes, a battery efficiency of 1,800mAh, a weight of 23kg, and a payload capacity of 16L, both 1.5 times that of the previous model MG-1P), and in November 2020, they have announced the next-generation model T30 (load capacity: 30L, working time: 16ha/h). On the other hand, these technological innovations are beginning to show signs of a lull. These companies are moving to lower prices and collaborating with fertilizer and seed manufacturers.

③ EU

(1) Academic level

- A project entitled PRENEMA at the University of Bern, Switzerland, is dealing with the triadic system of the subsurface in natural and field ecosystems and is promoting chemical profiling of substances released by plants when exposed to predators.
- Turlings et al. at the University of Neuchâtel, Switzerland, have been conducting fundamental research on the application of the underground tripartite system involving HIPVs to agroecosystems for pest control. They have identified Caryophyllene, a component that attracts nematodes, in the three-way system of rice crops (maize), root-feeding larvae of the Hammidae family, and nematodes that parasitize and kill the larvae[37].
- Using various modeling techniques, Beerling et al. at the University of Sheffield in the U.K. estimated that spreading crushed rock containing silicon on agricultural land can improve the soil and help sequester atmospheric CO2 in the soil on a large scale. According to the simulation, the effect of atmospheric CO2 sequestration in soil was particularly pronounced in large CO2 emitting countries, such as the United States and China[38].
- From the perspective of integrated pest management, a group at the Rothamsted Arable Crops Research Institute in the UK has proposed a method called Push-Pullstrategies. They have conducted demonstration tests of its effectiveness in Africa and have obtained promising results.
- As for sensor technology, active research and development is being conducted mainly by Leti in France, Fraunhofer-Gesellschaft in Germany (especially ISIT, IPMS, and ENAS institutes), VTT in Finland, and CSMC in Switzerland[20].

(2) Commercial level (the Netherlands)

- The Netherlands possesses a land area about the size of Kyushu and has narrowed down its production items as a country and accumulated cultivation technology and know-how for large-scale, high-yield horticulture, which has made the country the second largest exporter of agricultural products in the world (tomatoes, bell peppers, and cucumbers account for 80% of the country's horticulture). Focusing on tomato cultivation in particular, which has one of the highest standards globally, the Netherlands has established a high-yield, large-scale cultivation model with a yield five times higher than that of Japan (70t/10a in the Netherlands, 15t/10a in Japan) and a farmland area per farmer (*Facility Horticulture) about 10 times larger (2.2ha in the Netherlands, 0.2ha in Japan)[39]. The technological superiority of Dutch facility horticulture can be divided into three elements: materials, hardware, and software.
- In terms of materials, the Netherlands has established the world's first rockwool nutrient cultivation, carbon dioxide application, and breeding and branching techniques suitable for equipment.
- In terms of hardware, high productivity is supported by the spread of technologies such as large-scale Fenloe greenhouses, hydroponic facilities, and automated equipment suitable for large-scale facilities (labor productivity in tomato production is nine times higher than in Japan).
- Furthermore, in the area of software, complex environmental control technology using computers has been developed. Since the world's first horticultural computer was introduced to the market by the company Hoogendoorn in 1974, Dutch companies Priva, Hoogendoorn, and Hortimax have been among the first to successfully commercialize advanced integrated control, including nonlinear control that sets complex indicators (e.g., satiation, etc.), which directly affects the reproductive growth of plants. This is the first time commercialization of advanced integrated control has been successful.
- At present, advanced greenhouse control with AI functions is also advancing in terms of practical use. In this field in particular, the Netherlands has a high technological advantage. In Japan, where only 2.5% of facilities are currently equipped with environmental control systems, the majority of similar facilities in the Netherlands have already implemented them, which indicates the large difference in the accumulation of know-how[40].

④ Israel

- Israel has historically focused on improving its food self-sufficiency, partly due to its relations with neighboring countries. Since much of its land is covered by desert, Israel has been developing advanced agricultural technologies to produce vegetables efficiently even under harsh conditions. Apart from Seedo Corp, which has developed fully automated plant factories for home and industrial use, Tevel Aerobotics Technologies' automatic harvesting robots (which uses drones), and A.A.A Taranis Visual's technology for detecting pests and diseases using remote sensing and AI image analysis technology have all attracted worldwide attention[41)].

The comparison of Japan's R&D level with that of other countries can be summarized as follows.

① Developing advanced sensor technology

- Sensor technologies (for physical sensors) regarding temperature, humidity, etc. are already obsolete, so what differences may exist among different countries is insignificant. Moreover, in the area of image analysis, companies in many countries continue to work on improving the accuracy of their image analyses, so no one company in particular can be said to be ahead of the rest.
- Japanese device and module manufacturers are highly competent, boasting strengths in elastic wave filters, inertial sensors for automobiles, etc. However, R&D for device and product commercialization is sluggish. Although industry-academia collaborations and individual R&D are progressing, conventional Japanese-style R&D cannot keep up with the global pace. In addition, the number of venture businesses in this area is low.
  Sensors in which Japanese companies have strengths are as follows.

- ✓ Dai-ichi Seiko: Odor sensor using ferroelectric and sensing membranes
- ✓ Taiyo Yuden: MEMS and odor sensing membranes
- ✓ Panasonic: Integrated molecular sensors with multiple channels and sensing membranes
- ✓ AromaBit: Sensor and sensing membranes
- ✓ Konica Minolta: Combination of multiple metal oxide sensors

② Developing automation technology

China currently has the most advanced agricultural drone technology. On the other hand, in the field of other agricultural machinery and robotics, Kubota, Yanmar, Iseki, and other Japanese companies are actively developing machinery, mainly for rice, and maintain world-leading technologies. Japan has a global advantage and is ahead in the field of automatic operation in the field of agricultural machinery, with fully unmanned agricultural machinery (level 3) expected to be implemented around 2023, for mountainous regions (level 3) around 2028, and for vegetables, field crops, and fruit trees around 2030. Through the widespread use of robotic farming machines, we aim to realize data-driven agriculture using growth models for each region. As for harvesting robots, research and development is becoming ever more active in Japan with the participation of start-up companies, such as Inaho and Agrist.

③ Developing new plant breeds

The DNA marker assisted selection breeding method has been developed to efficiently select useful new breeds by identifying the nucleotide sequence information of genes involved in useful traits for agricultural production. Seeds from Japanese companies, such as Takii Seeds and Sakata Seeds, are used in many countries around the world. In the field of genome editing technology, which has been attracting attention in recent years, the basic patents for CRISPR/Cas9 and other technologies have been suppressed by foreign countries. However, under the framework of the Cross-ministerial Strategic Innovation Promotion Program (SIP), the wisdom of domestic universities and related research institutions will be concentrated to strategically promote related research and development, develop as intellectual property domestically produced genome editing technology as well as tools (application technology) optimized for the characteristics of specific crops, and establish an environment that facilitates the use of these technologies by the domestic seed industry, etc. This technology has already made it possible to maximize the functional components of crops (increasing value) and to pinpoint and improve inconvenient traits in cultivation (reducing cost). GABA tomatoes developed by the University of Tsukuba and potatoes free of natural toxins developed by RIKEN are examples of the advancement of such technologies for vegetables and fruit trees[42)].

④ Development of cultivation techniques that do not rely on chemical fertilizers and pesticides and that minimize environmental impact

- Japan's domestic market is no more exciting than overseas markets and its development speed is inferior to that of EU companies. However, despite this situation, companies' efforts are becoming more active[43)]. For example, the petroleum company Idemitsu Kosan is co-developing with the group company SDS Biotech a new large-scale pharmaceutical. Also, Sumitomo Chemical has transferred its biological pesticide business to the group company Behrendt Bioscience and is strengthening its structure by transferring control of its biological pesticide business, including R&D and overseas sales channel development, also to Behrendt Bioscience.
- As a national project, the JST Moonshot Goal 5 has been launched: "Creation of the industry that enables sustainable global food supply by exploiting unused biological resources by 2050." This MS Goal places particular emphasis on the use of microorganisms and the speed of its research in Japan is expected to accelerate in the near future[44)].

⑤ Developing technologies that optimize the balance among crop growth, yield and cultivation environment

With regard to rice, research on genetic materials, crop models, and paddy community microclimate models continues to accumulate, and although a certain degree of superiority is recognized regarding Japan's know-how (see below), the gap with other countries is shrinking. In terms of algorithm development with actual agricultural use in mind, the mainstream approach is to construct a "smart food chain" that extends to production, processing, distribution, and consumption by linking machines and data from various manufacturers through the Agricultural Data Collaboration Platform (WAGRI), but widespread use of this approach is likely to take some time.

- The "Climate Change Impact Assessment for Agriculture and Forestry (A-8)" (FY2013-2017), a project commissioned by the Ministry of Agriculture, Forestry and Fisheries (MAFF), elucidated the mechanism of high temperature and high CO2 impact on crops through rice FACE experiments, future projections of crop yield and quality based on climate scenarios using crop models, and quantitative evaluation of adaptation technologies. It additionally conducted quantitative evaluation of adaptation technologies.
- In the "Development of Production Stabilization Technology to Adapt to Global Warming (A-11)" (FY2015-2019), research is being conducted on the mutual effects of changes in soil fertility, temperature, and atmospheric CO2 concentration on rice growth and yield.
- The ministry of Education, Culture, Sports, Science and Technology (MEXT)'s program SI-CAT (Social Implementation Program on Climate Change Adaptation Technology) (FY2015-2019), projected the yield and quality of rice based on the latest climate scenarios using crop models and evaluating adaptation measures as well as provided support for local governments to formulate climate change adaptation plans using the results. Currently, climate change impact prediction and assessment of adaptation measures for crops using the latest climate scenarios and advanced crop models are still underway under Theme 2 ("Projection of Climate Change Impacts and Evaluation of Adaptation Options for Agriculture, Forestry and Fisheries") of the Ministry of the Environment's S18 "Comprehensive Research on Projection of Climate Change Impacts and Adaptation Evaluation." Regarding JST/CREST's "Plant Robustness" (FY2015-2022), some of the R&D in this area focused on phenomics, which has improved our understanding of outdoor crop dynamics. These include the development of methods for designing breeds that adapt to environmental changes through hybrid modeling, analysis of physiological and ecological responses of crops with a focus on photosynthesis, analysis using omics such as the transcriptome, evaluation of interactions between crops and

other organisms such as insects, and analysis focusing on interactions between soil microbes and crops.

- Some of the aims of JST and Presto's "Functions and Regulation of Plant Molecules" (FY2020-2025) were to understand the communication between plants and other organisms from a chemical ecology perspective.
- A study has been published in which artificial plant communication was successfully created in soybean fields by wafting the smell of cuttings of surrounding weeds (*Solidago altissima*) to improve crop resistance to insect pests as well as yield. It has also been reported that this exposure increases the content of isoflavones and saponins in soybean seeds.
- Furthermore, in recent years, a model developed mainly by the National Agriculture and Food Research Organization (NARO) has been used to predict future rice yield and quality deterioration risk across Japan based on climate projection scenarios[11]. The models developed so far are currently being analyzed for factors of uncertainty and improved prediction accuracy within the framework of the international Agricultural Model Intercomparison and Improvement Project (AgMIP)[12].

⑥ Plant factories

In terms of fully artificially-lit plant factories, Japan boasts the world's top knowledge and technological superiority (see below), though the technological gap with other countries has been narrowing in recent years. Since market potential is expected to be greater overseas than domestically, technology exports in cooperation with other regions of the world are expected to advance.

- Robotic and AI technologies for large-scale production (2014-present): In 2014, LED lighting was fully adopted in a plant factory producing 10,000 plants per day by a university venture (Mirai Inc. and others). Also in 2014, the Ministry of Economy, Trade and Industry's Innovation Center Establishment Assistance Program (Osaka Prefecture University and others) introduced the most advanced technologies at the time, including seedling sorting and automatic transplanting robots that focus on circadian rhythms in plant factories, automatic transport equipment for cultivation rooms, direct airflow systems to each cultivation shelf, and multi-color LED light sources.
- VITEC ENESTA (CO., LTD.) and others in 2017, 7-Eleven and Mitsubishi Chemical in 2018, and Tokyo Electric Power Company Holdings in 2019 announced the construction of large-scale plant factories producing tens of thousands of plants per day.
- Environmentally adaptive plant design systems based on predictive models of plant growth and environmental responses (2015-present): Based on the Ministry of Education, Culture, Sports, Science and Technology (MEXT)'s H27 (FY2015) strategic objective of

“establishing environmentally-adaptive-plant design systems for stable food supply in the age of climate change,” CREST’s “Plant Robustness” (FY2015-2022), PRESTO’s “Control of Field-Grown Plants” (FY2015-2020), and the “Cultivation with Information Science” (FY2015-2020) all use their plant factories or cultivation technologies as direct research targets or research test facilities.

- As an applied technology project commissioned by the Ministry of Agriculture, Forestry and Fisheries (MAFF), research and development on the optimization of agricultural production in solar-powered plant factories using plant biometric information and AI is being conducted under the “Future Artificial Intelligence Agriculture Creation Project” (2017-2021) (development of AI-based technology for optimizing cultivation and labor management [by a consortium of seven corporations with Ehime University as the core institution]).
- In 2017, “leading research on plant phenomics and its application using artificial intelligence technology (NPO Japan Plant Factory Association, AIST, Kajima Corporation, Chiba University)” was selected as a part of NEDO’s “leading research for social implementation of next-generation artificial intelligence technology.” This project aims to comprehensively and quantitatively understand the characteristics and yields of horticultural crops, such as lettuce and other plants, and to develop phenotyping technology using artificial intelligence that analyzes the dynamic effects of environmental factors necessary for growth. In addition, by developing and making available an infrastructure for the utilization of plant phenotyping, this project aimed to realize a technology that can be applied to production activities in plant factories and, in the future, breeding.

In addition, many of the respondents to this survey said that Japan is actually the most advanced country in terms of knowledge on plant physiology, which is necessary for all of the above technological developments. Japan’s superiority on this point is due in large part to the fact that Japan has a long north-south territory and varying climates, which allows for a wide variety of cultivated products and methods for adapting to varying environmental conditions. As a result, as mentioned above, Japanese seed and seedling manufacturers have a strong presence in the world, with Japanese agricultural chemical manufacturers holding more than 50% of the world’s uncommercialized agricultural chemicals.

	Japan	U.S	EU	China	Israel
① Sensing	○	○	○	◎	○

② Automation technology	○	○	○	○	○
③ New plant breeds	△	◎	△	◎	△
④ New fertilizers and pesticides	△	△	◎	△	△
⑤ Optimization	△	○	○	○	○
⑥ Plant factories	○	○	◎	△	◎

III. Plan for Realization

1. Area and field of challenging R&D, research subject for realization of the Goals

① The fields and areas where challenging R&D should be promoted are as follows.

(1) PS (Plant Speaking): Developing sensor technology to acquire high-dimensional information (gene expression, protein synthesis, etc.) from inside plants that can be transmitted in real time.

(2) PR (Plant Recipe): By fully utilizing the sensing information in (1) and visualizing the information inside the plant, a highly accurate algorithm measuring the relationship between crop growth and the external environment can be developed. In terms of output, we will construct an unconventional plant cultivation system to introduce high-dimensional plant prescriptions into plants that will no longer rely on the conventional chemical fertilizers, chemical pesticides, and biostimulant materials currently under development.

(3) PO (Plant Optimization): We will develop next-generation plant factories as cultivation sites that maximize the technological effects of (1) and (2) and produce a large number of plant species from around the world without being affected by climate change and with minimal environmental impact, thereby ensuring food and nutrition for all mankind. In addition, by creating a package that can be moved, produced at sea, and even produced in space, we can realize a world in which anyone can grow anything, anytime, anywhere, without being affected by climate change.

② Research issues to be addressed in order to achieve the goals

(1) PS (Plant Speaking):

We have listed in section Ⅱ-2-① several issues regarding the development of advanced sensor technologies, but the challenging development area we would like to discuss here is the advancement of molecular sensors. Among the following research subjects, it is important to conduct research and development from the viewpoint of improving practicality. It was difficult because sensors were not small enough for introducing to plant, and network was un suitable in agricultural fields. Nowadays, semiconductor has been minimized rapidly, as a result, many kinds of sensors are also minimized, moreover, 5G technology has been established. Under this back ground, we can approach PS.

- Improving accuracy: Realizing pre-use calibration and low-cost surface cleaning.
- Improving durability: Technology needs to be developed to reduce power consumption, improve physical (hardware) durability, and allow functioning despite harsh growing environments.
- Miniaturization: At present, physical sensors can be miniaturized to the order of 0.1m, but when considering the introduction of foliar spraying as described below, miniaturization to the order of 10 μ to 50 μ is necessary. The key to miniaturization is the use of multiple layers (miniaturization) of semiconductors. In line with the so-called Moore's Law of technological advancement, sensor technology achieved dramatic improvements in performance in the late 1900s. However, regarding the introduction of sensors to plants, insufficient miniaturization means single-function sensors are the best we can do at present. On the other hand, as miniaturization progresses, it will become possible to introduce sensors with multiple functions and to output the information processed in the sensor[45)].
- Higher order and comprehensiveness: In addition to obtaining single information on metabolites, genes, and proteins, it is necessary to obtain comprehensive information that includes existing sensing information such as temperature.

(2) PR (Plant Recipe):

As described in section II-2-④, it is clearly necessary to establish a means for reducing or replacing conventional chemical fertilizers and pesticides, but through this review, it is clear that completely replacing biofertilizers, biopesticides, and biostimulants is difficult.

In conventional agriculture, ammonia-derived nitrogen fertilizer is applied and absorbed by plants in the form of nitrate nitrogen, which is then planted and converted into amino acids and proteins as appropriate. Conventionally, it is known that the number of flowers and nutrient contents are controlled by the binding of specific proteins to specific receptors at specific times and sites (leaves, roots, etc.) in the plant growth process. In the past, it was difficult to obtain real-time physiological data from plant internals, but with the development of the PS technology described above, it will be possible to determine when to introduce relatively expensive substances, such as amino acids and proteins. Based on this information can be used to pinpoint the formulation of amino acids and proteins in plants, thereby making it possible to secure profitability even when introducing expensive amino acids and proteins. The following are specific issues to be addressed regarding PR.

- Improving the efficiency of multivariate analysis technology: Development of next-generation quantum computers and of mathematical models that measure phenotyping (of plant shape, color, temperature, odor, composition, leaf movement, etc.), extract features, and calculate optimal algorithms for plant cultivation.

- Establishing introduction methods: Until now, no method existed for introducing relatively large molecules, such as proteins and amino acids, directly into plant bodies. However, several research groups have recently reported a method of introducing such molecules by binding them to metal nanoparticles. Unfortunately, it is still unknown whether the introduced substances will actually function as intended in the plant body. In addition, the optimization of the substances that serve to lead the introduction of proteins and amino acids into the plant body will also be an issue in the future[47)48)].
- Establishing prescription combination technology: This refers to the development of technology to store multiple amino acids and proteins in capsule-like particles and bind them to metal particles. For example, if a group of proteins necessary for genome editing and transgenes are packaged and introduced into a capsule, real-time genome editing in accordance with environmental changes will be possible.

(3) PO (Plant Optimization):

Even if innovative cultivation methods are established in accordance with items (1) and (2) above, there is always a risk that the algorithm will not function properly due to errors caused by changes in the external environment, as typically occurs in conventional agriculture. We have high hopes for completely closed plant factories as a means to solve this problem. In particular, we would like to focus on the following challenging development issues. Plant factories has been started to study 40 years ago in Japan, and now, a lot of companies enter this market. However, most of them is suffered from deficit, in other words, related technology is immature[49)]. Nowadays, each technology has been rapidly, therefore, there is enough possibility to return to profit by integrated these each technology, and developed seed and the other agricultural materials designated for using in plant factories.

- Developing technologies that help diversify locations: Even today, technological developments are being made to set up plant factories in a variety of locations and spaces. For example, the company Forward Thinking Agriculture (Spain) has developed a plant factory that can be operated at sea. The Nichiei Intec Group (Japan), Agri Wave (Japan), and Alesca Life Technologies (Hong Kong) have developed container-type plant factories for use in urban areas. Additionally, JAXA has proposed plant factories as lunar farms. In the future, we would like to accelerate these efforts and create an environment where highly profitable agriculture can be carried out in any location[50)51)52)53)54)].
- Integration of various technologies: In addition to making full use of the new cultivation technologies developed for PS and PR, we will automate the cultivation and production process using work machines and robots and select plant breeds that will increase the

efficiency of crop cultivation in plant factories to the utmost limit.

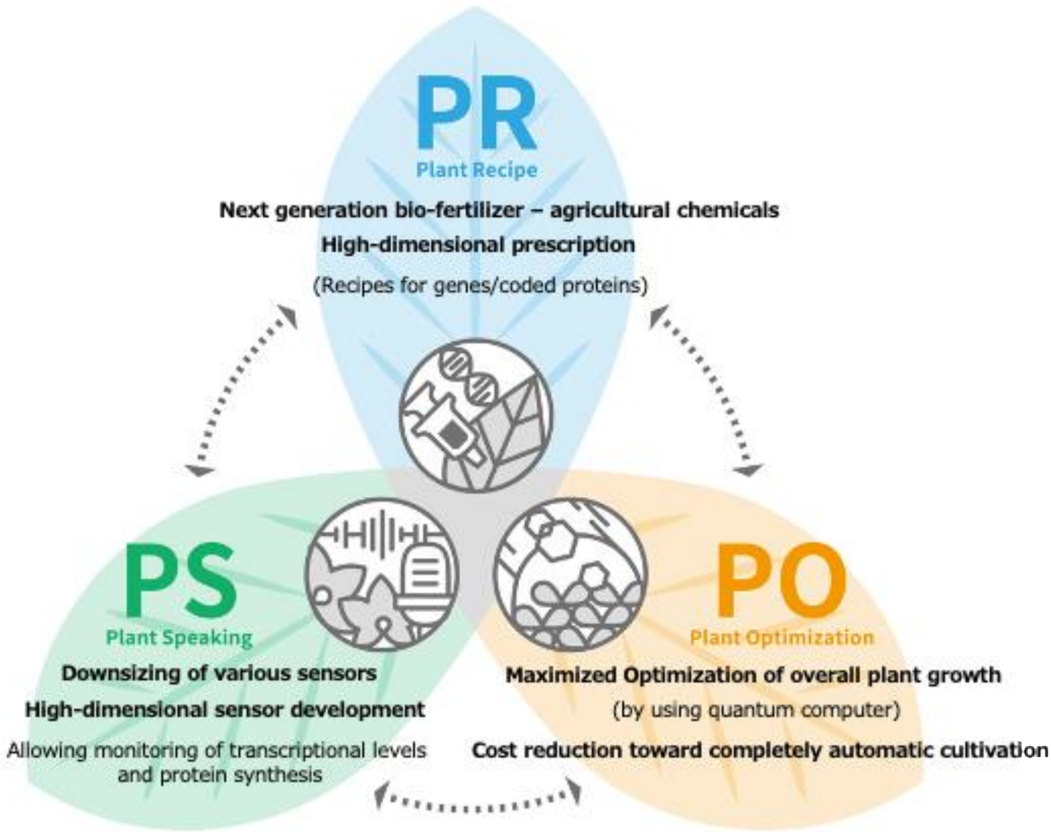

Fig. Fields/areas and research topics of challenging research and development

2. Direction of R&D for realization of the goals

(Targets [milestones] to be achieved in 2030, 2040, and 2050 respectively, R&D for achieving these milestones, and ripple effects.)

① Specific targets (milestones) to be achieved and those that are expected to be achieved in *2030*, *2040*, and *2050*, respectively

＜PS＞

(1) 2030: A small molecular sensor will have been completed that may actually be introduced into plants at the laboratory level, thereby creating an environment in which acquiring information from inside plants is possible.

(2) 2040: With the introduction of molecular sensors into actual agricultural fields, the level of monitoring of plant growth will be dramatically improved and new physiological mechanisms of plants will be reported one after another.

(3) 2050: Power generation technology using sensors successfully introduced into plant bodies

＜PR＞

(1) 2030: We will be able to develop algorithms based on phenotypic data and establish an organization that can conduct collaborative research on a series of processes up to the incorporation of cultivation methods. In addition, an environment will have been established in which multiple environmental factors can be artificially manipulated at once to obtain phenotype data, and the accuracy of the quantum computer required for algorithm development will have been improved.
(2) 2040: Technology for introducing high-dimensional substances will have been established along with algorithms for indicating new plant cultivation methods based on information from PS being developed one after another.
(3) 2050: The technology for simultaneous formulation of multiple proteins will have been established. In addition to the ability to control complex plant metabolic mechanisms, it will also be possible to edit genomes in real time according to environmental changes. In addition, plants will be used to extract various useful substances and as a raw material for bioethanol.

＜PO＞
(1) 2030: The linkage of existing technologies will be enhanced and technologies will be developed that allow plant factories to be operated more profitably under all kinds of conditions.
(2) 2040: Cultivation based on the new methods established in PR begins.
(3) 2050: The profitability of plant factories will have been dramatically improved through the full utilization of the technology established in PR. Technology that contributes to diversification of locations will have also been established with the proliferation of plant factories advancing worldwide.

② Specific R&D themes to be addressed to achieve the milestones.
(Descriptions of the milestones for *2030*, *2040*, and *2050*, respectively)
＜PS＞
(1) 2030:
- Improved accuracy: Realizing pre-use calibration and low-cost surface cleaning.
- Miniaturization: At present, physical sensors can be miniaturized to the order of 0.1m, but when considering the introduction of foliar spraying as described below, miniaturization to the order of 10μ to 50μ is necessary. The key to miniaturization is the use of multiple layers (miniaturization) of semiconductors. In line with the so-called Moore's Law of technological advancement, sensor technology achieved dramatic improvements in performance in the late 1900s. However, regarding the introduction of sensors to plants, insufficient miniaturization means single-function sensors are the best we can do at present. On the other hand, as miniaturization progresses, it will become

possible to introduce sensors with multiple functions and to output the information processed in the sensor.

- Sensing detail: Developing sensing technology for detecting specific chemical compound and base, and obtaining the information of metabolic products and genome.

(2) 2040:

- Improved durability: Technology must be developed to reduce power consumption, improve physical (hardware) durability, and to function despite harsh growing environments.
- Sensing detail: Development of more sophisticated sensing compounds, and development and coverage of sensing technologies for genes and peptides.

(3) 2050:

- Establishing power generation technology using sensors introduced into the plant body: We would like to develop technology to convert various types of energy (wind-induced, metabolic, hydraulic, etc.) that may be generated during the plant cultivation process into electricity and other forms of energy that are easy for humans to use[54)].

＜PR＞

(1) 2030:

- Improving the efficiency of multivariate analysis technology: Development of next-generation quantum computers and of mathematical models that measure phenotyping (of plant shape, color, temperature, odor, composition, leaf movement, etc.), extract features, and calculate optimal algorithms for plant cultivation.
- Developing for new technology in order to introduce high quality materials to plant.

(2) 2040:

- Establishing introduction methods: Until now, no method existed for introducing relatively large molecules, such as proteins and amino acids, directly into plant bodies.
- Establishment of post-installation control: Unfortunately, it is still unknown whether the introduced substances will actually function as intended in the plant body. In addition, the optimization of the substances that serve to lead the introduction of proteins and amino acids into the plant body will also be an issue in the future.
- Establishing prescription algorithms: Based on the information from PS, a series of algorithms will be developed to demonstrate new cultivation methods for introducing new materials, such as proteins and amino acids, into plants.

(3) 2050:

- Establishing prescription combination technology: This refers to the development of technology to store multiple amino acids and proteins in capsule-like particles and bind them to metal particles. For example, if a group of proteins necessary for genome editing and transgenes are packaged and introduced into a capsule, real-time genome editing in accordance with environmental changes will be possible.

- Considering applications other than food: We will pursue the possibility of applying substances to be introduced into plants for purposes other than the efficient growth of agricultural products. For example, the mass production of specific chemical substances (raw materials for pharmaceuticals, plastics, etc.) using plants[55)56)], research aimed at maximizing the efficiency of plants used for bioethanol rather than for food, and the possibility of developing energy using the metabolic energy of plants.

＜PO＞

(1) 2030:

- Integration of various technologies: In addition to making full use of existing materials, we will automate the cultivation and production process using work equipment/robots, and select breeds that are designed for plant factory cultivation, thereby maximizing the efficiency of crop cultivation in plant factories.

(2) 2040:

- Integration (upgrading) of various technologies: In addition to making full use of the new cultivation technologies developed in PS and PR, we will select breeds for plant factory cultivation by automating the cultivation and production processes using work equipment and robots, and will increase the efficiency of crop cultivation in plant factories to the utmost limit.

(3) 2050:

- Integration (upgrading) of various technologies: In addition to making full use of the new cultivation technologies developed in PS and PR, we will select breeds for plant factory cultivation by automating the cultivation and production processes using work equipment and robots, and will increase the efficiency of crop cultivation in plant factories to the utmost limit.
- Development of technologies that contribute to location diversification: This particular goal must be done on an ongoing basis, but as mentioned above, we would like to promote research and development so that plant factories that can be operated on the sea, container-type plant factories that can be used in urban areas, and plant factories that can be used as lunar farms can be put to practical use.

③ Effects of achieving milestones on society

(Descriptions of milestones for *2030*, *2040*, and *2050*, respectively)

＜2030＞

- The miniaturization technology of molecular sensors to be developed in PS can be applied not only to agriculture, but also to livestock breeding, fishery, and the medical world, thereby contributing to the elucidation of the biological mechanisms of all living things.
- Since smooth collaboration between industry, academia, and government is essential for the advancement of PR, achieving this milestone will help eliminate waste and inefficiency in R&D.
- The development of PO will drive collaboration among research institutes as well as the above-mentioned PR, ultimately driving their technological innovation in a way that involves many industries.
- Overall, the number of options for all manner of plant cultivation will increase. In particular, options for environmentally friendly cultivation methods will be more plentiful, some of which will be put to practical use, which will lead to agricultural production with a lower environmental impact than before and will partly contribute to halting global environmental change.

＜2040＞

- As it becomes possible to introduce various technologies at relatively low cost, farmers who are able to make full use of them will be able to manage large tracts of farmland with a smaller number of people than before, with some farmers improving their profitability considerably. On the other hand, the majority of farmers who did not adopt the technology will continue to polarize and decline, except for those who target a few niche areas. As a result, the industrial structure around agriculture may change drastically (the number of farmers who do not go through JA will increase, the number of farmers who can make contracts with retailers and restaurants on equal footing will increase, Japanese agricultural exports will increase, etc.).
- The establishment of a new market for plant formulations and a full-fledged market for plant factories will contribute to the development of supporting industries, such as reagent manufacturers, materials manufacturers, and machinery manufacturers. It has also been suggested that plant factories can be used as bases for recharging renewable energy sources, so they can be seen as a technology that drives the use of renewable energy as well.
- Advanced sensing technology using PS will make it possible to measure information in plants other than crops in real time, and we will begin to use plant sensing data to predict the occurrence of disasters caused by recent global environmental changes.

＜2050＞

Japan's PS and PR technologies, packaged as PO, will be actively exported to overseas markets to help create a world in which anyone can grow anything, anytime, anywhere.

- An environment in which agriculture can be sufficiently developed in each country will be created. This will facilitate the establishment of social security programs, such as "basic food," which will provide a foundation upon which people may live a more dignified life.
- Contributing to the dramatic reduction of food mileage and the realization of a decarbonized society.
- Technological innovation in PR will redefine the concept of breeding.
- By replacing all chemicals and energy sources with plant-derived products, we can accelerate the decarbonization of society from several angles. We will realize a progressive life for mankind without unreasonable waste.

Challenging Research & Development	By 2030	By 2040	By 2050
"Plant Speaking (**PS**)" Precisely understand plant body's internal information • *In vivo* information (Temperature, pH, genes, metabolites) • Sensing (Down-sizing, upgrading, imaging)	<Goal> ✓ Measurement of plant internal temperature and pH <Research & Development> ✓ Downsizing <Spillover effect> ✓ Other fields apart from agricultural section would be able to obtain in vivo information	<Goal> ✓ Analyses of plant internal metabolites and nucleic acids information <Research & Development> ✓ Functional upgrading ✓ Durability <Spillover effect> ✓ Prediction of disaster via high-sensing technology	<Goal> ✓ Introduction of of low-cost technology use to other fields apart from agricultural section <Research & Development> ✓ Application enlargement aside from agricultural crop production <Spillover effect> ✓ Generation of green energy from plants
"Plant Recipes (**PR**)" Prescription based on plant body's internal information • High-dimensional prescription for genes and coded protein • Algorithm maximization	<Goal> ✓ Selection of useful biofertilizers <Research & Development> ✓ Development of ultra-dispersive and permeable materials ✓ Development of optimal algorithm <Spillover effect> ✓ Novel evaluating methods for fertilizer & agricultural chemicals and formation of industry institution	<Goal> ✓ Development of next-generation fertilizers and agricultural chemicals derived from genes/coded protein <Research & Development> ✓ Development of coding gene, amino acid and peptide insertion techniques <Spillover effect> ✓ Massive improvement of plant productivity	<Goal> ✓ Instantaneously use of optimal prescription <Research & Development> ✓ Development of real-time genome editing technology <Spillover effect> ✓ Replacement of plant breeding concept
"Plant Optimization (**PO**)" Bringing out plant's maximum potential for crop cultivation • Portable type (low-cost) • Energy circulation (water, light, electricity) • Fully automated system • Environmental control (water, light, temperature, CO_2)	<Goal> ✓ Use of technology for cultivation efficiency improvement <Research & Development> ✓ Automation of current technology ✓ Development of new materials (e.g. wood) <Spillover effect> ✓ Technology innovations for other fields apart from agricultural section	<Goal> ✓ Use of PS/PR technology to improve cultivation efficiency <Research & Development> ✓ Automation of PS/PR technology ✓ Cost-reduction via using new materials <Spillover effect> ✓ Technological innovations in other fields apart from agricultural section	<Goal> ✓ Generate the most suitable environment for 'any plants' at 'anywhere' <Research & Development> ✓ Development of moon-surface, ocean and vertical agricultural technology <Spillover effect> ✓ Space farming, ocean farming and vertical farming

Fig. Targets to be achieved in 2030, 2040, and 2050, research and development aimed at achieving the milestones, and ripple effects.

3. International cooperation

- PS and PR will be technologies that can be commonly used in all plant species and all cultivation environments. As mentioned above, we believe that Japan can conduct fundamental research in a way that is compatible with its relatively wide range of plant species and cultivation environments. However, the smooth transfer of technology will only be achieved in the end by conducting localization with research institutions and companies in other countries. We also believe it is important to collaborate with research institutes and companies in each country at the fundamental research level in order to develop products that meet the regulations of each country.

- As for PO, collaboration with other countries is rather difficult because of differences in the main crop species and cultivation environments of each country, so each country will have to promote research on its own main crop. However, there is no doubt that Japan is currently one of the leading countries in the world in terms of historical material development technology. Taking advantage of this strength, Japan is expected to function as the world's database for crop cultivation by analyzing data and developing algorithms not only for its own cultivars but for many other crop species as well.

4. Interdisciplinary cooperation

① Political and legal cooperation

As described in further detail below in section Ⅲ-5ELSL, political and legal backing is essential to achieve this Moonshot Goal. This is because agriculture as an industry has long been protected by governments, and in exchange, it has been built on a variety of regulations. As mentioned above, agriculture will be reborn as a highly productive industry by the year 2050. Therefore, in exchange for reducing subsidies, we would like to establish a framework for deregulation and flexible introduction of new technologies.

② Collaboration with local communities

While this section overlaps with section ① above, agriculture as an industry is highly regulated by local communities[60]. For example, the application of pesticides cannot be done freely and young new farmers are often prohibited from renting or buying land[61]. Moreover, there is no sharing of information on what, how much, and how other agricultural producers in the region produce, and to whom they sell their products. As a result, inefficiencies occur, such as the continued production of unprofitable agricultural products and individual ownership of agricultural equipment that could be shared. Therefore, we consider the following initiatives to be necessary for 2050.

(1) Ensuring appropriate independence: Each agricultural producer should be permitted to carry out his or her own cultivation plan in accordance with his or her own business plan. Also, based on the premise that Japan's food self-sufficiency rate cannot be improved without making full use of limited farmland, new farmers must be allowed to enter the industry.

(2) Constructing an information sharing system based on economic rationale: Since we are discussing businesses, it is unrealistic for each producer to share all the information they may

possess, but it is desirable to build a system where information sharing is more active than it has been, for example, for the purpose of establishing joint shipping and leasing schemes for agricultural machinery. In addition, as the number of new agricultural materials increases, information on these materials should be shared to the extent allowed by economic activities. This will lead to the accumulation of information on what is most appropriate to use and when to use it in a particular region, thereby maximizing profits over the medium to long term.

③ Collaboration with educational institutions

As seen in the case of genetic modification and genome editing, people's reticence regarding the introduction of science and technology into food is significant[62]. It is true that in some cases, the research side provides insufficient information and poor explanations, but there are also many people who seem to be opposed on largely emotional grounds. Not only with regard to food, hesitation concerning the introduction of new technology into society is inevitable, and yet, our society's current economic development would not be possible without the progress of science and technology. When a new technology is introduced, only educational institutions can teach people how to make sense—and use—of the technology for themselves. Since the speed of progress in science and technology is expected to accelerate in the future, it is necessary to establish a place where people can be educated on the correct way to interact with science and technology from an early stage of their education.

④ Strengthening industry-academic collaboration

(1) Above all in the field of agriculture, the knowledge of plant physiology and cultivation that is researched in academia has not been disseminated to the agricultural industry due to poor connections between the two. With the premise that PS and other technologies will be put to practical use, agriculture will have more room to utilize the power of science than ever before. Therefore, it is necessary to make active efforts to better materialize the knowledge acquired in academia in the future.

(2) As can be said for any data business in general, from the standpoint of data users (in this case, mainly agricultural producers), it is desirable to collect as much data as possible in one place along with a system that enables mutual analysis of that data. In order to achieve this, it is desirable to build a system in which each company and industry can store data in a highly compatible manner without monopolizing it and that also allows users to freely utilize the data.

5. ELSI (Ethical, Legal, Social Issues)

(1) Establishing a system for the active use of science and technology:

Deregulation and promotion of agriculture-related technologies: This is an issue that is common to other industries as well, but deregulation is essential. As for genome editing, it has been decided that some of the technologies can be put on the market simply with notification and publication, but it has been a long time since that discussion started. However, a long time has passed since the start of discussions. A result of that oversight is that the speed of research in Japan remains stagnant, meaning most of the related patents are concentrated in the U.S. and China[62]. Moreover, the registration process for agricultural chemicals is very complicated and takes at least five years to complete according to a former employee of an agricultural chemical manufacturer. The development of new formulations is expected to continue in the future, but if it takes too long to review each case, it will be difficult for Japanese companies to maintain their competitive advantage in the fast-paced, borderless business environment of today's world. Since agriculture-related technologies affect food and, by extension, human lives, there are many situations where careful decisions are necessary, we would like the Ministry of Agriculture, Forestry and Fisheries (MAFF) and other government agencies to formulate clear criteria that will enable them to judge whether each technology should be implemented with as much speed as possible or whether extra time is necessary to assess the risks.

(2) Adjusting the balance of imports and exports:
If Japan and other countries that have traditionally relied on imports for much of their food supply become able to secure a greater amount of food for themselves, it is highly likely that they will need to make some kind of adjustment with the United States, Russia, Brazil, and other countries that currently earn large profits from exporting agricultural products. Some experts have expressed great concern about upsetting the balance of food trade, but from the following perspectives, we believe that the project should nevertheless be promoted.

- As a function of the state, providing a stable supply of food to its people is a primary issue that can never be overlooked, but countries that rely on imports for most of their food needs should urgently review their structures.
- For food transportation, the indicator used is food mileage, which is a numerical value calculated by multiplying the amount of food by the distance it is transported. Countries that import a large amount of food, such as Japan, show an overwhelmingly large value (i.e., environmental impact) compared to countries with a high food self-sufficiency rate[63].

(3) Reducing psychological hurdles to science and technology for general consumers
Consumers often react negatively about any kind of human manipulation particularly of things they put into their bodies, such as food. However, without pesticides, it would be impossible to produce enough food to feed the current world population, and mutations caused by genome editing, with a few exceptions, can occur naturally anyway (mutations that can also

occur in normal breeding). Governments, universities, companies, and the media must work together to make public announcements and appeal to consumers correctly based on these facts. In addition, since education from an early age is essential for fostering this kind of attitude, the role of educational institutions is significant.

IV. Conclusion

Our team has knowledge of when, where, and what can be administered to plants to increase yield and nutritional value. Initially, we had to consider how to make this knowledge available to the world. What was difficult to discuss in the verification process was who exactly needs to increase food production and for whom. Additional difficulties include the fact that international trade is already established amidst a complex political and social equilibrium, meaning unforeseen increases in food production could upset that equilibrium. Even so, the world is still not well supplied with food and appears even less so when we look ahead to the next 50 years. In this research report, we discussed how nations and humanity should be ideally when it comes to food production and provision. As a result, we have come to the conclusion that, in order for a nation to be a nation, it should be able to procure its own food independently. On the individual level, though more than 50 years have passed since Maslow articulated the five hierarchical levels of physiological needs, we have come to the additional conclusion that a society should be considered fundamentally unjust if it fails to even meet its people's primary and secondary needs, which is why we have set this particular MS Goal in the first place.

In terms of the science and technology needed to achieve our goals, we interviewed experts from a wide range of fields both in Japan and overseas in three areas: sensing, next-generation materials, and automation. We concluded that technological innovation in the so-called smart agriculture field, which is the main area of automation, has progressed more than we had initially expected, and that the main area of concern now is essentially cost reduction and UI/UX improvement for practical use. On the other hand, the speed of technological innovation in agricultural materials is slow, partly due to insufficient understanding of plant body information; we believe that the room for technological innovation is large. Therefore, we have concluded that we can achieve this goal by combining the above three areas of PS (plant speaking), PR (plant recipe), and PO (plant optimization) with the hardware technologies that are already in practical use for labor saving and automation as well as by drastically improving the efficiency of agricultural production through intensive scientific and technological development.

In addition, through this survey and interviews, we became convinced that plants, farmland, and agricultural production activities contain many elements and that approaching this goal will not only solve food problems, but will also allow us to approach a wider range of social issues. In particular, we reaffirmed that we can play a very important role in solving energy problems and realizing a decarbonized society. In this sense, we would like to continue to hold discussions with people from a wide range of industries and sectors, not limited to the food and agriculture industry, and contribute to the solution of many social problems as ripple effects of solving this goal.

V. References

1)国際連合広報センター：https://www.unic.or.jp/news_press/info/33789/

2) unicef ：https://www.unicef.or.jp/news/2020/0173.html

3)United States Department of Agriculture Foreign Agricultural Service ：https://apps.fas.usda.gov/psdonline/app/index.html#/app/home

4) 農林水産省　農業生産活動に伴う環境影響について（2004 年）：https://www.maff.go.jp/j/council/seisaku/kikaku/bukai/10/pdf/h160514_03_siryo.pdf

5) 農林水産省企画部会 地球温暖化の進展による農業生産等への影響（2014 年）：https://jsite.mhlw.go.jp/fukushima-roudoukyoku/content/contents/000622407.pdf

6) 農林水産省　我が国における穀物等の輸入の現状（2020 年）：https://www.maff.go.jp/j/saigai/n_coronavirus/pdf/yunyu.pdf

7)cook pad　コロナ禍前後での家庭の料理に関する実態調査（2021 年）：http://workey.jp/comparison?id=28&comparison_type=2

8)POCKET MARCHE ：https://www.pocket-marche.com/news/202010291000690/

9)食べチョク：https://www.tabechoku.com/about

10)野村総合研究所（NRI）　マズローの欲求階層説：https://www.nri.com/jp/knowledge/glossary/lst/ma/maslow

11)環境省脱炭素ポータル：https://ondankataisaku.env.go.jp/carbon_neutral/

12)Rakuten 楽天証券：https://www.rakuten-sec.co.jp/web/special/worldcaprank/

13)JETRO 世界の特許出願件数増加を中国が牽引（2020）：https://www.jetro.go.jp/biz/areareports/2020/aa7990dd4a98275f.html

14) John Helliwell., et al., World Happiness Report（2021）：https://worldhappiness.report/ed/2021/

15)農林水産省 食料自給率及び食料自給力の検証（2019）：https://www.maff.go.jp/j/council/seisaku/kikaku/bukai/attach/pdf/kikaku_1112-11.pdf

16)農林水産省　諸外国の食料自給率等（2017 年）：https://www.maff.go.jp/j/zyukyu/zikyu_ritu/attach/pdf/013-2.pdf

17)IBM 環境を守る新しいプラスチックを作る―原料は植物バイオマス。使用後は用途に応じて分解速度をコントロール（2020）：https://www.ibm.com/blogs/think/jp-ja/mugendai-11672-interview-biodegradable-biomass-plastics/

18) 大澤 良 植物育種の歴史とゲノム編集技術への期待（2020）：https://www.maff.go.jp/j/syouan/nouan/carta/tetuduki/attach/pdf/201225_sympo-17.pdf

19)JST 俯瞰報告書 ライフサイエンス・臨床医学分野（2021）：file:///C:/Users/shiny/OneDrive/%E3%83%89%E3%82%AD%E3%83%A5%E3%83%A1%E3%83%B3%E3%83%88/Sacmots/Moonshot/JST%E3%83%AC%E3%83%9D%E3%83%BC%E3%83%88/CRDS-FY2020-FR-04_20200.pdf

20) JST 俯瞰報告書 ナノテクノロジー・材料分野（2021）：CRDS-FY2020-FR-03.pdf

(jst.go.jp)
21) S. L. Gilhespy et al., “First 20 years of DNDC（DeNitrification DeComposition）: Modelevolution”, Ecol. Model 292（2014）：51-62. doi: 10.1016/j.ecolmodel.2014.09.004
22) 矢野経済　種苗ビジネスの市場実態と将来展望 ～食糧生産の根幹を形作る世界と日本の種苗マーケット（2021 年）
23) 藤巻 宏 “緑の革命 とその後” 熱 帯 農 業 44(3):206-212（2000）：
https://www.jstage.jst.go.jp/article/jsta1957/44/3/44_3_206/_pdf
24) 農林水産省生産局環境保全型農業対策室　環境保全を重視した農法への転換を促進するための施策のあり方（１）（2008）：
https://www.maff.go.jp/j/study/kankyo_hozen/07/pdf/data3.pdf
25) 経済産業省　平成 28 年度 地域経済産業活性化対策調査、植物工場産業の新たな事業展開と社会的・経済的意義に関する調査事業 報告書（2016）：
https://www.meti.go.jp/meti_lib/report/H28FY/000810.pdf
26)巌佐 庸 数理生物学入門―生物社会のダイナミックスを探る 東京：共立出版（1998）
https://ci.nii.ac.jp/ncid/BN05344975
27)A. Satake et al., “Forecasting flowering phenology under climate warming by modelling theregulatory dynamics of flowering-time genes”, Nat. Commun. 4, no. 1（2013）：2303. doi：10.1038/ncomms3303
28）M. Seki et al., “Adjustment of the Arabidopsis circadian oscillator by sugar signalling dictatesthe regulation of starch metabolism”, Sci Rep 7, no. 1（2017）：8305. doi 10.1038/s41598-017-08325-y
29)矢野経済 2020 年版 植物工場の市場実態と 将来展望（2021）
30）J. Sun et al., “FACE-ing the global change: Opportunities for improvement in photosynthetic ra-diation use efficiency and crop yield”, Plant. Sci. 177, no. 6（2009）: 511-522. doi:10.1016/j.plantsci.2009.08.003
31) P. F. South et al., “Synthetic glycolate metabolism pathways stimulate crop growth and productivity in the field”, Science 363, no. 6422（2019）: eaat9077. doi: 10.1126/science.aat9077
32) C. Muller et al., “The global gridded crop model intercomparison phase 1 simulation dataset”, Scientific Data 6, no. 1（2019）: e50. doi: 10.10388/s41597-019-0023-8
33) ＜２０２０年 版 ＞スマート農業 の現状 と将来展望～省 力 化 ・高 品 質 生 産 を実 現する農 業 ＩｏＴ・精 密 農 業 ・農 業 ロボットの方 向 性～（2021）
34)FarmLogs：https://farmlogs.com/
35) Deere and company：https://www.deere.com/%20deere.com
36) Jane Lanhee Lee U.S. vertical farms are racing against the sun （ 2019 ）
https://www.reuters.com/article/us-vertical-farms-growth-idUSKCN1U010H
37) S. Rasmann et al., “Recruitment of entomopathogenic nematodes by insect-damaged

maize roots", Nature 434（2005）: 732-737. doi: 10.1038.nature03451
38) D. J. Beerling et al., "Potential for large-scale CO2 removal via enhanced rock weathering with croplands", Nature 583, no. 7815（2020）: 242-248. doi: 10.1038/s41586-020-2448-9
39) 農林水産省　施設園芸をめぐる情勢（2021）：https://www.maff.go.jp/j/seisan/ryutu/engei/sisetsu/attach/pdf/index-39.pdf
40) 三輪　泰史　オランダ農業の競争力強化戦略を踏まえた日本農業の活性化策　JRＩレビュー Vol.5, No.15（2014）：https://www.jri.co.jp/MediaLibrary/file/report/jrireview/pdf/7372.pdf
41) 佐藤 光泰, 石井 佑基 2030 年のフード&アグリテック ―農と食の未来を変える世界の先進ビジネス 70（2020）
42)矢野経済 苗ビジネスの市場実態と将来展望 ～食糧生産の根幹を形作る世界と日本の種苗マーケット～ ＜2020 年版＞（2021）
43)矢野経済　農薬産業白書＜2020 年版＞（2021）
44) 内閣府　ムーンショット型研究開発制度　ムーンショット目標 5：https://www8.cao.go.jp/cstp/moonshot/sub5.html
45) 大阪大学　大学院情報科学研究科　三浦研究室：http://www-ise3.ist.osaka-u.ac.jp/%E7%A0%94%E7%A9%B6%E5%86%85%E5%AE%B9/%E7%B2%89%E6%9C%AB%E3%82%B3%E3%83%B3%E3%83%94%E3%83%A5%E3%83%BC%E3%82%BF/
46) RenatoGrillo et al., "Foliage adhesion and interactions with particulate delivery systems for plant nanobionics and intelligent agriculture" nanotoday vol.37（2021）：https://doi.org/10.1016/j.nantod.2021.101078
47) Pramod Mahajan et al., "Effect of Nano-ZnO Particle Suspension on Growth of Mung (Vigna radiata) and Gram (Cicer arietinum) Seedlings Using Plant Agar Method" Journal of nanotechnology（2011）：https://www.hindawi.com/journals/jnt/2011/696535/
48) Kang Wang et al., "Uptake, translocation and biotransformation of selenium nanoparticles in rice seedlings(Oryza sativa L.) " Wang et al. J Nanobiotechnol（2020）：https://jnanobiotechnology.biomedcentral.com/track/pdf/10.1186/s12951-020-00659-6.pdf
49) 一般社団法人日本施設園芸協会（2016）：https://www.alic.go.jp/content/000127162.pdf52)植物工場・農業ビジネス online 海上に浮かぶ未来の植物工場・食料生産基地（2015）：http://innoplex.org/archives/28360
50)日栄インテック（株）植物工場：https://www.nichieiintec.jp/plants/1820.html
51)アグリウェーブ（株）：http://agri-wave.com/agw/index.php
52) Alesca Life Technologies Limited：https://www.alescalife.com/ja/
53) 植物工場・農業ビジネス online JAXA 宇宙探査ハブ、日本の植物工場を活用した「月面農場」に関する報告書を公開（2019）：http://innoplex.org/archives/47735
54) Lingyi Lan et al., Breathable Nanogenerators for an On-Plant Self-Powered Sustainable

Agriculture System (2021) ACS Nano : https://pubs.acs.org/doi/10.1021/acsnano.0c10817
55) 環境省「プラスチック資源循環戦略」の策定について（2019） https://www.env.go.jp/press/106866.html
56)内閣府　バイオ戦略（2020）：https://www8.cao.go.jp/cstp/bio/index.html
57)農林水産省　第 3 章 地域社会の維持や地域の安全・活性化を目指した「地域政策」（2013）：https://www.maff.go.jp/j/council/seisaku/nousin/bukai/h25_4/pdf/siryou1_2_3_1.pdf
58) 一般社団法人全国農業会議所全国新規就農相談センター新規参入者の経営資源の確保に関する調査結果（2019）：https://www.be-farmer.jp/uploads/statistics/RyxYJETfbUww65nf3VzZ202003171448.pdf
59)毎日新聞　ゲノム編集食品「食べたくない」4 割　東大調査　今夏にも解禁（2021）：https://mainichi.jp/articles/20190605/k00/00m/040/193000c
60)独立行政法人科学技術振興機構　研究開発戦略センター　調査報告書　ゲノム編集技術（2014）：https://www.jst.go.jp/crds/pdf/2014/RR/CRDS-FY2014-RR-06.pdf