Mobilizing Science, Technology, and Innovation to Transform Japanese Agriculture

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The agricultural sector in Japan is currently undergoing drastic changes. A comparison of statistical data for the years 1980 to 2016 shows that gross agricultural production decreased from 10.3 trillion yen to 8.8 trillion yen, agricultural land decreased from 5.46 million hectares (ha) to 4.47 million ha, the working population in the agricultural sector decreased from 6.97 million to 1.92 million, and the food self-sufficiency rate decreased from 53% to 39%, indicating a clear contracting tendency for agriculture in Japan. Moreover, the total area of farmland that has been abandoned because small-scale farmers quit or did not have a successor has increased from 123,000 ha to 284,000 ha, and the average age of farmers has greatly increased—reaching 66.8 years old in 2016. As a response to these trends, there has been an accumulation of agricultural land for specific core farmers,[1] a trend that is expected to continue. Japanese agriculture is thus drastically changing from small-scale farming to large-scale farming with fewer workers. However, complex farmland structures with numerous small independent farms still remain in many places, making the productivity of agriculture in Japan low compared with that of other developed countries.

Japanese agriculture: The current state and policy objectives

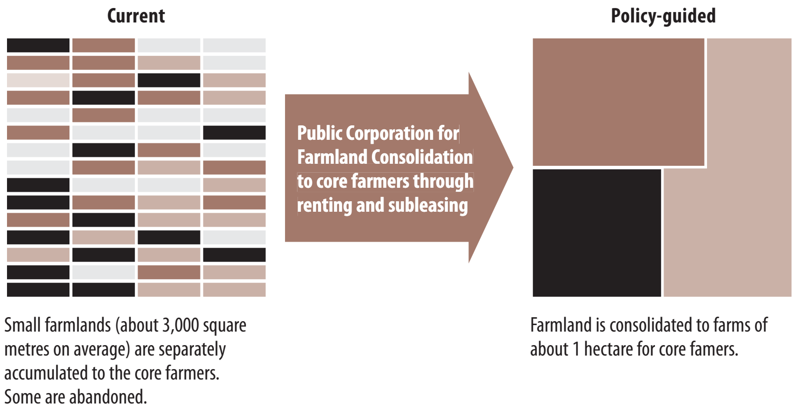
In 2013, the Japanese government initiated the Japan Revitalization Strategy, a new growth strategy to overcome two decades of economic stagnation since 1990. With regard to agriculture, the government stated that its objective was to make agriculture, forestry, and fishery a growing industry, and it set key performance indicators (KPIs) (Box 1), such as an increase in the ratio of farmland used by business farmers to 80% in the next 10 years (ending in 2023). In order to achieve this objective, the government established a new organization called the Public Corporation for Farmland Consolidation to Core Farmers through Renting and Subleasing in 2014 (Figure 1). This organization rents separated small areas of farmland or uncultivated land from quitting farmers and consolidates small areas, if needed, to provide large-scale farmland for core farmers. In 2015, the farmland area utilized by core farmers increased by 80,000 ha,

Box 1: Key performance indicators for agriculture in the Japan Revitalization Strategy

- Increase the ratio of farmland used by business farmers to 80% in the next 10 years (ending in 2023); this was 48.7% as of the end of Fiscal Year 2013.
- Reduce the cost of rice production by business farmers by 40% in the next 10 years (ending in 2023) over the current national average cost, including through efforts by industry on aspects of materials and distribution. The national average cost of rice production in 2011 was ¥16,001/60 kg.
- Increase the number of corporate farmers fourfold from the 2010 level to 50,000 in the next 10 years (ending in 2023). In 2010 there were 12,511 farming corporations.
- Expand the size of the agriculture sector based on the collaboration of primary, secondary, and tertiary sectors of the economy (called the 'sixth industrialization of Agriculture, Forestry and Fisheries') to ¥10 trillion in 2020.
- With regard to dairy farming, increase the number of projects to promote collaboration among the primary, secondary, and tertiary sectors to 500 by 2020.
- Increase the value of exports of Agricultural, Forestry and Fishery products and foods to ¥1 trillion before 2020, the initial target year.

Source: Japan Revitalization Strategy, 2013; see http://www.kantei.go.jp/jp/singi/keizaisaisei/pdf/en_saikou_jpn_hon.pdf.

Figure 1: Farmland consolidation through public corporation



Source: Based on MAFF, with permission, available at http://www.maff.go.jp/j/keiei/koukai/kikou/attach/pdf/index-39.pdf (in Japanese).

Note: Because the average age of farmers has greatly increased and small-scale farmers have been quitting, the accumulation of farmlands to core farmers is in progress. In many cases, small farmlands are separated and so cannot be used by core farmers, thus inhibiting the improvement of productivity. To solve this problem, public corporations that rent farmland from quitting farmers and sublease to core farmers are established in each prefecture. Under this scheme, farmland owners will be paid by the corporation, and the corporation will consolidate the small farmlands into one large area, which it subleases to core farmers.

indicating that the accumulation of farmlands to the core farmers is progressing properly.

To promote the transition to large-scale farming, Japan's agricultural land law was amended to ease regulations for possession of farmland by a farming company (the new law was implemented on 1 April 2016). Of the four conditions (company style, business style, constituent members or voting rights, and board members) required for companies to own farmland, the last two were eased, allowing farming companies to be scaled up. The new law eases the promotion of investment into farming companies, which is expected to eventually make Japanese business farms larger. This will contribute to reaching another KPI formulated in the Japan Revitalization Strategy: 'Increase the number of corporate farmers fourfold from the 2010 level to 50,000 in the next 10 years (ending in 2023)'.

Another KPI in that strategy is a reduction by 40% of the cost of rice production by business farmers in the next 10 years (ending in 2023) compared with the current national average cost,[2] including through efforts by industry on aspects of materials and distribution. It seems to be difficult to reach this number using only policy tools. Investment in research and technology development is critical in this circumstance.

Since the structure of Japanese agriculture is evolving to large-scale farming, technology that supports this transition is needed. Two main technical problems face this trend in land use–based agriculture. First, automation technology for farm operations is needed to expand the limit of farmland use per person, which is critically important for large-scale farming. Second, the establishment of an efficient farm management system is needed for appropriate farm work plans to enable the management of many separated small-scale farms with multiple crop varieties to spread out harvest timing.

In fact, the Cross-ministerial Strategic Innovation Promotion Program (SIP)[3]—a national program for science, technology, and innovation initiated in 2013 by the Council for Science, Technology and Innovation—aims to confront the most important societal challenges facing Japan, as well as to contribute to the resurgence of the Japanese economy. The SIP has become a powerful tool to address these challenges. Indeed, the project entitled 'Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries'[4] is among 11 projects selected for the SIP.[5]

One of the main goals of this project is to increase the income of farmers by using innovative technology for smart farming and to enhance the value of agricultural products, working with agricultural policy making to introduce farmland structural reform, and expanding the size of agriculture-related industry (e.g., seedling industry).

The project has identified two major ways to reach these goals:

1. Incorporate robotics, information and communication technologies (ICTs), genome information, and other leading-edge technologies to produce a uniquely Japanese smart, ultra-labour-saving, and highly productive agriculture model.

2. Enhance the value of agricultural, forestry, and fishery products by developing new materials and offering distinct, functional health foods and other products, using techniques from medicine and engineering.

Finally, in 2016 the Japanese government formulated its 5th Science and Technology Basic Plan.[6] In this document, the government proposes the living concept 'Society 5.0', where ICTs, which have recently significantly advanced, will be fully utilized for the benefit of all citizens. Eleven projects in the SIP have been assigned as to explore the concept of Society 5.0, including the project

Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries.

Research on smart agriculture: An overview

Recently research deploying the Internet of Things (IoT), big data, and artificial intelligence (AI) has been galvanized. In the SIP project Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries, these novel technologies are also integrated into the research activity for developing next-generation technologies that boost the productivity of Japanese agriculture.

To establish a large-scale smart farming system for rice production, automation technology needs to be developed. An efficient farm management system for appropriate farm work plans that enable the management of many separated small farms is also needed to reduce rice production costs. In this SIP project, two types of end users are considered: core farmers with family-style farms (of about 30 ha) and company farmers with larger farms (about 100 ha).

Research is being carried out to develop cultivation techniques based on automatically driven farm equipment, an automated water control system for paddy fields, a farming assistance system based on space assessment information, a precise automated fertilization system with sensing soil fertility for each farm, and a farming plan simulation system that enables efficient farm work in many small separated farms. Research is also being carried out to develop ground-breaking varieties of crops—such as crops with super high productivity, using various techniques such as genome-editing technology—and to enhance the value of agricultural products based on scientific evidence for health (brain function and body locomotive function, etc.). By developing these technologies, the area of farm land per person is expected to expand from 12 ha to about 24 ha, thus removing factors limiting farm size for core farmers.

These technologies include an automatic driving system for farm equipment that is expected to contribute to the expansion of working farmland per person by using geometric space information generated by precise Global Positioning System (GPS) technology. This will enable work to be done at night as well as performed simultaneously by multiple types of equipment. Automatic driving systems for tractors and unstaffed work system products (with human monitoring) will be put on the market by 2018, when the Quasi-Zenith Satellite System service will become available. Moreover, an unstaffed automatic driving system with remote monitoring that can cross fields is under development and expected to be ready by 2020. Ensuring that safety guidelines are met is an ongoing effort of the Ministry of Agriculture, Forestry and Fisheries. A first-of-its-kind system for working large fields was developed successfully in 2016. Four automatic robot-tractors are used in this system to boost work efficiency. These tractors can work together with location error of less than 4 centimetres. Although tractor systems for large fields in Western countries have adverse effects on plant growth because of the high pressure exerted by tractors on the soil, the Japanese system does not have this problem, and farm work plans can therefore be designed to be flexible by changing the number of tractors being used.

To control water in paddy fields, farmers manually change the water level by using valves. Developing labour-saving technology is therefore needed. Core farmers have to manage many small areas of farmland that have been abandoned by small-scale farmers. Core farmers plant different varieties of rice to distribute the harvesting timing, resulting in a significant increase in the burden of water management. To address this issue, research is now being conducted to develop an automated remote-controlled water control system. Automated valve-controlling equipment with a water-level sensor and networking equipment for wireless control have so far been developed. Water level–sensing data are stored in a cloud service, and farmers can remotely monitor these data and set the desired water level with a smart phone or tablet. This technology enables a 50% to 90% reduction in labour required for water control, which accounts for about 30% of rice paddy farm work. The technology is therefore expected to contribute to a significant increase in the area of farmland that can be used per person.

Technologies for an automated multi-robot tractor system or automated water control system for paddy fields need farm work plans based on precise farmland information such as specific data on crop growth, climate, water level, temperature, and so on. In the SIP Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries project, technologies for collecting data on crop growth (nitrogen content, chlorophyll content, etc.) and soil fertility from many small separated farmland areas are being developed to maximize appropriate harvest timing and efficient fertilization. Satellites or drones are used to obtain these data. A system that generates maps over an area of 3,000 square kilometres for a crop's protein content or the appropriate harvest timing for rice has been developed. Farmers or farming advisors can obtain information at any time from this system by using a tablet or smart phone. The information enables quality control of products, and the system has been used for a branding strategy for local rice labels such as 'Seiten no Hekireki' in Aomori Prefecture and 'Tuya Hime' in Yamagata Prefecture. Research is also being conducted to develop a sensing system that uses a drone equipped with a spectroscopic sensor or thermal imaging sensor and a controlling module. Information about visible light, near-infrared light, or thermal infrared light can be used to estimate nitrogen content, chlorophyll content, photosynthesis activity, and water stress. Based on this information, a diagnostic algorithm for accurately estimating plant growth is now being established.

Information about farmland such as data on plant growth, soil fertility, and climate data obtained by various sensors must be appropriately selected and processed before providing the results to farmers. Therefore a system for managing many farmlands that integrates and processes information from multiple systems and generates a farming plan according to each farmer's strategy is now being developed. Elements of this system—including technologies such as an automatic driving system, an automated water-control system, and a farming plan simulation system—have been integrated into a single package of technologies and introduced to representative farmers in Chiba Prefecture. This enables the optimization made possible by using multiple technologies that comprise a single system and assessment of integrated technologies from the viewpoint of management. This approach is also effective for obtaining feedback from users, which can lead to practical improvements of the integrated technologies. The newly developed technologies are expected to be used widely by Japanese rice farmers.

Many types of sensing systems for obtaining climate information on soil fertility, water level, temperature, and so on in paddy fields are connected to the Internet, and numerous data collected by these sensing systems will be accumulated in cyberspace. A data platform will be established and a huge amount of data about paddy fields will be available to everyone. These data can be analysed by AI or other tools, and data obtained every year will be utilized for further advanced cultivation technology.

In the field of horticulture, for example, environmental information—such as information on temperature, humidity, and CO_2 concentration inside a solar-powered plant factory—are collected by sensors connected to the Internet. These data are analysed together with biological data inside the tomato fruit obtained by cyclopaedic analysis of gene expression, metabolites, or other biological data. These integrated data will be utilized for environment control programmes to optimize the cultivating environment for tomatoes and other crops, enabling maximization of crop yield and controlling its quality to meet market requirements that may change on a daily basis. This novel technology will also be used to analyse the know-how of excellent farmers. Their techniques will be digitalized and provided to young farmers who have less experience with cultivation. These novel trials will enable a smooth transition of the cultivation techniques of experienced farmers to young farmers, and this is expected to help the Japanese agriculture industry to be competitive in the international market.

The future of crop breeding: Utilizing genome-editing technology

Recently, in addition to traditional breeding techniques, genome-editing technology that assists in making precise and targeted changes to the genome of living cells has been greatly advanced (the most significant of these techniques is the CRISPR/Cas9).[7] This is expected to be a driving force for the development of ground-breaking crop varieties that cannot be achieved by traditional breeding techniques, and is predicted to accelerate the development of new varieties with high capacity.

In the SIP's Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries, studies with mutagenesis induced by heavy ion beams or other mutagens have been carried out to elucidate specific genomic loci that are responsible for production traits and to apply them for developing new ground-breaking varieties. The SIP project has already obtained null-segregant rice plants in which genes responsible for grain size or number have been edited. These plants can contribute to the ground-breaking variety with super high yield.

In the near future, the isolation and characterization of useful genes that are responsible for the translocation of nutrient compositions will enable the development of more productive varieties with greater yield. In tomatoes, genes responsible for gamma-amino butyric acid (GABA) content and parthenocarpy or other traits are now being edited to create varieties that are free from the need for artificial pollination or have a high GABA content in order to reduce the farmer's hormone processing cost (for pollinating the plants) or to enhance the value of the products. Other major crops such as wheat, soybeans, potatoes, and so on have also been investigated as possible candidates for optimizing genome-editing conditions or creating ground-breaking varieties.

Because the CRISPR/Cas9-based technology and other existing genome-editing technology, such as TALEN-based technology, have already been patented mainly by universities in the United States of America and Germany, research is also being conducted to develop Japanese genome-editing technology. Technology that induces point mutations in the targeted genes, such as target-AID (activation-induced cytidine deaminase),[8] as well as technology utilizing a pentatricopeptide repeat (PPR) motif,[9] which can be designed to bind any specific DNA/RNA site, are under development. These technologies are also being examined for creating ground-breaking crop varieties, and they constitute an integral part of the SIP project. Internationally competitive crop varieties and agricultural products based on these technologies will be developed in the near future and will contribute to an increase in exports of Japanese agricultural products.

Living modified organisms (LMOs) are regulated by multiple laws in Japan, but primarily by the law on biosafety—the Law Concerning the Conservation and Sustainable Use of Biological Diversity through Regulations on the Use of Living Modified Organisms—which has been enacted to 'ensure the precise and smooth implementation of the Cartagena Protocol on Biosafety to the Convention on Biological Diversity'. In this Law, 'LMO' is defined as 'an organism that possesses nucleic acid, or a replicated product thereof, obtained through technologies for the processing of nucleic acid extracellularly or technologies for fusing of the cells of organisms belonging to different taxonomical families'.[10] Genome-editing technology can edit intended specific genomic sites without external nucleic acid or trace marks. Therefore there is no consistent decision as to whether genome-edited crops are subject to regulation or not. Considering this situation, research is also being conducted to develop a method to prove that the genome-edited crops do not possess extracellularly processed nucleic acid; methods for promoting consumer acceptance based on benefits are also being considered. Thus there is cooperation between administrative work and technology aiming at public acceptance of genome-edited agricultural products.

Conclusions

In the SIP project Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries, research on smart agriculture—especially research concerning rice production and the development of ground-breaking varieties—are ongoing towards the KPIs stated in the Japan Revitalization Strategy. By combining novel varieties that respond to consumers' needs with next-generation cultivation technology that utilizes ICTs and other cutting-edge technologies, the productivity of Japanese agriculture is expected to be greatly enhanced. These state-of-art technologies could also be introduced to developing countries, and are expected to contribute to tackling the global food supply problem in the future.

Notes

1 'Core farmer' is defined in Japanese agriculture policy as an 'efficient and stable farming management body such that the main workers' lifetime income and labor time are at a level similar to that of workers in other industries'.

2 The average cost of rice production in 2011 was 16,001 yen per 60 kilograms.

3 See http://www8.cao.go.jp/cstp/panhu/sip_english/sip_en.html.

4 For more information about the Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries project, see http://www8.cao.go.jp/cstp/panhu/sip_english/42-45.pdf.

5 The 2016 budget for the SIP Technologies for Creating Next-Generation Agriculture, Forestry and Fisheries was 2.925 billion yen. Other SIP projects and their budgets (billion yen) in 2016 are as follows:

- Innovative Combustion Technology: 1.9
- Next-Generation Power Electronics: 2.41
- Structural Materials for Innovation: 3.758
- Energy Carriers: 3.49
- Next-Generation Technology for Ocean Resources Exploration: 4.66
- Automated Driving System: 2.713
- Infrastructure Maintenance, Renovation, and Management: 3.156
- Enhancement of Societal Resiliency against Natural Disasters: 2.33
- Innovative Design/Manufacturing Technologies: 2.19
- Cyber-Security for Critical Infrastructure: 2.5

6 See http://www8.cao.go.jp/cstp/english/basic/5thbasicplan.pdf.

7 This technique uses RNA-guided endonucleases known as Cas9 from the microbial adaptive immune system named CRISPR (clustered regularly interspaced short palindromic repeats), which can target any genomic loci specified by short guide-RNA. See Hue et al., 2014, for more details.

8 Nishida et al., 2016.

9 Yagi et al., 2015 and Yagi et al., 2014.

10 See https://www.env.go.jp/en/laws/nature/law_ccsubdrlmo.pdf.

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