Moonshot International Symposium
December 18, 2019

Working Group 5

Innovation for future agriculture – satisfying both food production and environmental conservation

Initiative Report

Table of Contents

WG5 :Innovation for future agriculture –satisfying both food production and environmental conservation

EXECUTIVE SUMMARY

The agriculture, forestry and fisheries industries should naturally aim for sustainable acquisition of food through harmonization and co-existence with nature. However, under the current methods which only focus on production efficiency, it is no doubt in the future that 1) productive resources including fertilizers will eventually be depleted, 2) contamination of farmland and groundwater will be intensified, 3) useful insects against natural enemies will become extinct, 4) desertification and global warming will be accelerated. This negative spiral will make sustainable food supply difficult.

In order for mankind to maintain sustainable food supply in the future and increase food production according to the growth rate of the world population, it is essential to shift to a new agriculture, forestry and fisheries system, which enables the coexistence of both conservation and recovery of the global environment and increased food production. The future of mankind cannot be handed over to the next generation so easily without the creation of destructive innovation in this field.

In addition, it is necessary for us to reconsider consumer behavior in the future. Currently, social problems, such as the waste of large amount of food, and increases in obesity and lifestyle-related diseases are mainly occurring in developed countries. Therefore, it is necessary to take challenging actions that will expand globally through the creation of new solutions, to improve the consumer behavior of mankind in a sounder direction.

In this context, WG 5 specified the following three MS Goal Candidates in order to realize the future image of "Recovering our civilization and healthy global environment" which should be aimed for by the Moonshot Research & Development Program.

MS Goal Candidate 1: Overcome constraints to water, fertilizers, and other resources by fully utilizing the biological functions of nature by 2050.

MS Goal Candidate 2: Developing solutions to eliminate food loss and waste and promote rational, health-, and environment-conscious food consumption by 2050.

MS Goal Candidate 3: Establishing a Robust Agricultural, Forestry and Fisheries System Which Can Adapt to Sudden Weather Changes by 2040.

I. VISION AND PHILOSOPHY

1. The Moonshot 「Area」「Vision」 for setting MS 「Goals」 candidate

To date, we have been developing farmland, woodlands and oceans on the earth, and achieved increases in food production making full use of various technologies according to the growth rate of the world population. However, it has also brought about destruction of the natural environment and overhunting of natural resources causing various problems including degradation of soil caused by excessive use of chemical fertilizers and agricultural chemicals, and contamination of rivers and groundwater.

In recent years, the global warming due to greenhouse gases has intensified, and the reduction of such gases has become an urgent task. Globally, a quarter of the total emission of greenhouse gases including nitrous oxide (N_2O) and methane. is caused by the agricultural and forestry industries, and the use of land.

The agriculture, forestry and fisheries industries should aim for sustainable acquisition of food through harmony and co-existence with nature. However, using current methods which only focus on production efficiency, it is no doubt in the future that 1) productive resources including fertilizers will eventually be depleted, 2) contamination of farmland and groundwater will be intensified, 3) useful insects against natural enemies will become extinct, 4) desertification and global warming will be accelerated. The Negative spiral shown in Figure 1 will make sustainable food supply difficult on a global scale.

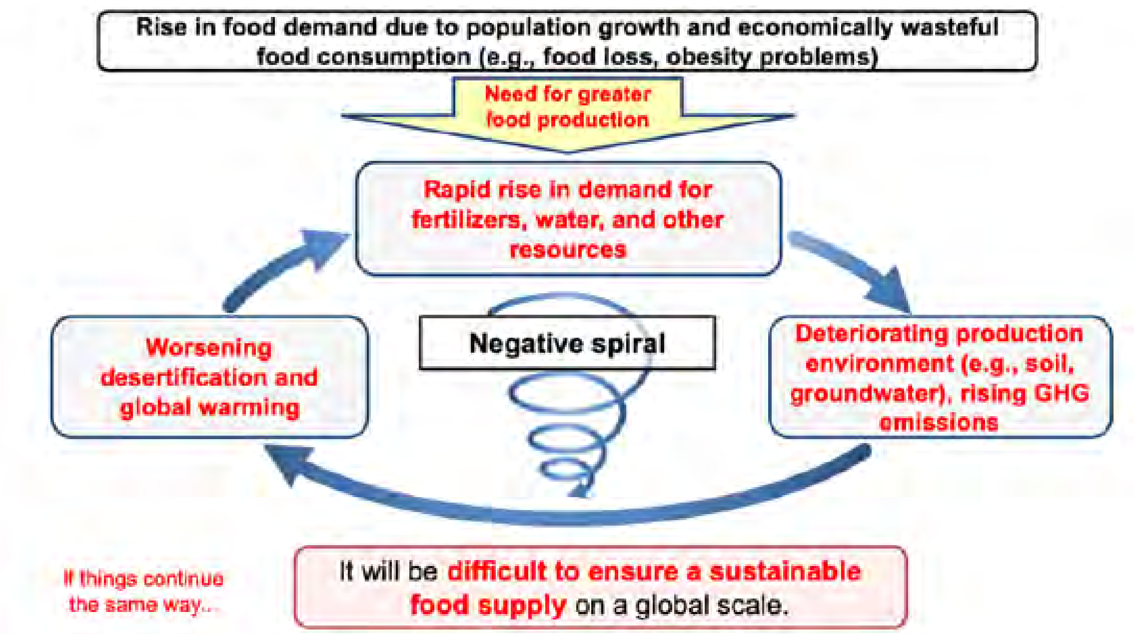

Figure 1　Anticipated social issues in 2050

Therefore, in order for mankind to maintain sustainable food supply in the future and increase food production according to the growth rate of the world population, it is essential to shift to a new agriculture, forestry and fisheries system, which enables the coexistence of both conservation and recovery of the global environment and increased food production. The future of mankind cannot be handed over to the next generation so easily without the creation of destructive innovation in this field.

In addition, it is necessary for us to reconsider consumer behavior in the future. Currently, social problems, such as the waste of large amount of food, and the increase in obesity and lifestyle-related diseases are mainly occurring in developed countries. Therefore, it is necessary to take challenging actions that will expand globally through the creation of new solutions, to improve consumer behavior in a sounder direction.

WG5 :Innovation for future agriculture –satisfying both food production and environmental conservation

In September 2015, the Sustainable Development Goal (SDGs) were adopted at the United Nations Summit. In the SDGs, the necessity of the following items was agreed to, and international cooperation activities have started towards the realization of these goals (Refer to Table 1 on Page 11).

(1) Sustainable agriculture with high adaptability for maintenance of the ecosystems and climate change must be accelerated (Goal 2)

(2) Conservation of mountain ecosystems including conservation of biodiversity must be promoted by drastically increasing reforestation, etc. on a global scale (Goal 15)

(3) Ocean and marine resources must be conserved, and utilized in a sustainable form (Goal 14)

(4) Sustainable production and consumption form must be secured through the reduction of food waste and food loss (Goal 12)

Based on such a background, in order to realize the future image of "Recovery for global environment and growth of civilization" which should be aimed for by the Moonshot Research & Development Program (refer to the following), WG 5 will hold discussions regarding the following three MS Goal Candidates with a vision, such as creating a new food production system which will enable both an "expansion of the amount of food supply" according to the growth rate of the world population, and "conservation of the global environment."

MS Goal Candidate 1: Overcome constraints to water, fertilizers, and other resources by fully utilizing the biological functions of nature by 2050.

MS Goal Candidate 2: Developing solutions to eliminate food loss and waste and promote rational, health-, and environment-conscious food consumption by 2050.

MS Goal Candidate 3: Establishing a Robust Agricultural, Forestry and Fisheries System Which Can Adapt to Sudden Weather Changes by 2040.

(Reference) Moonshot Research and Development Program - Future Visions & Ambitious Goals - (July 31, 2019, Drafted by Visionary Council)

The visionary council, which consists of experts, proposed the 3 Areas, 13 Visions, and examples of 25 MS Goals that Moonshot Research and Development Program should aim for. The aim is to set ambitious targets and concepts for a social agenda that are difficult to tackle but will have profound impact once resolved. (See Figure 2)

Working Group 5 discusses the following Area and Visions for setting MS Goals candidate.

[Area]

- *Turning the aging society into the innovative and sustainable society by harnessing diversity through techno-social transformation*
- *Recovery for global environment and growth of civilization*

[Vision]

- *Industrial transformation by complete automation*
- *Sustainable Resources Circulation*
- *Harmonization with nature*

[Examples of MS Goal candidate to be used as reference]

７) *Full automation of agriculture, forestry ＆ fisheries (by 2040)*

１３) *Elimination of food loss (by 2050)*

１６) *Harmonization between agriculture and biodiversity (by 2050)*

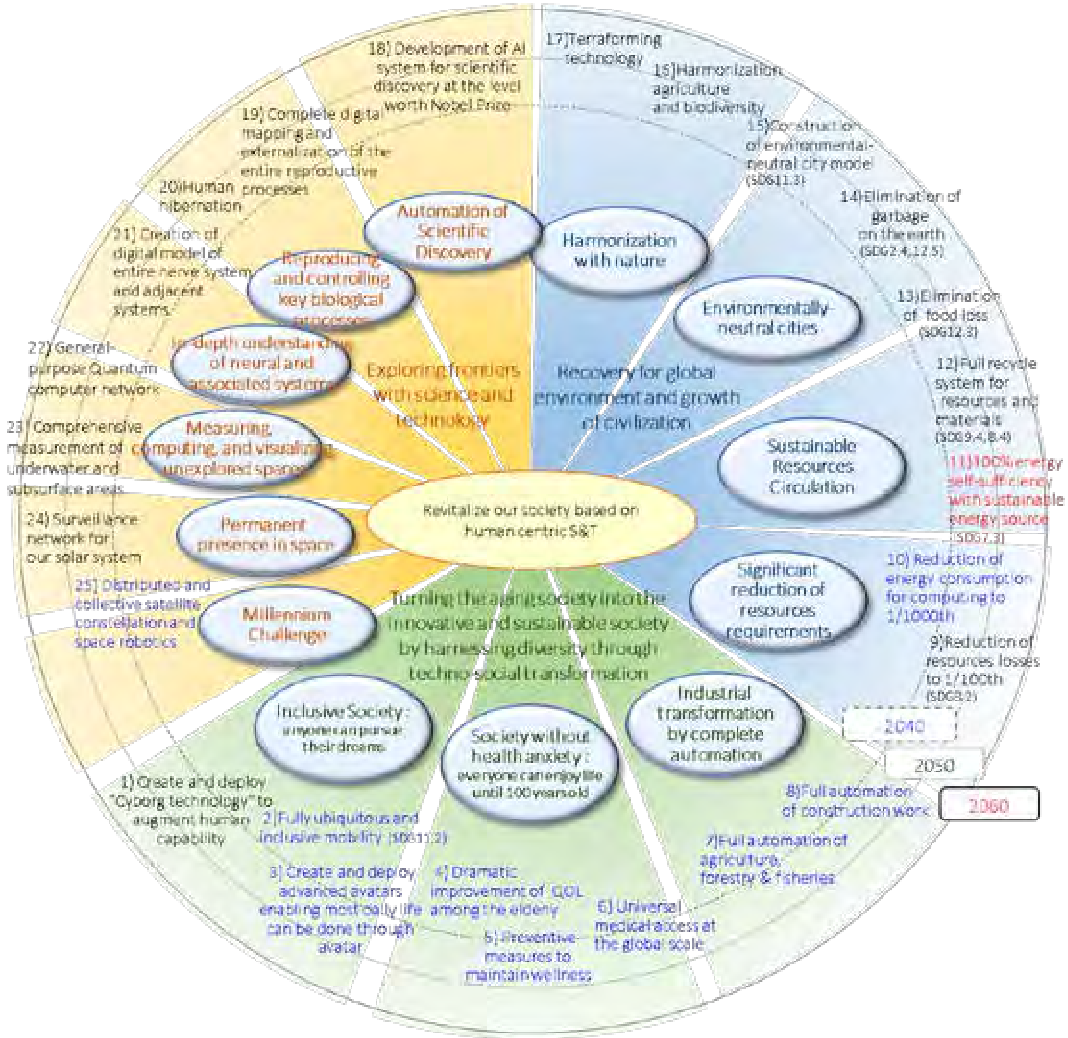

Figure 2 Future visions and 25 MS goal examples

2. Concept of MS Goal candidate

In order to create novel food production systems that can both increase human food supply in accordance with the increase in world population, and conserve the global environment, it is necessary to 1) realize strong agriculture, forestry, and fisheries in which it is possible to make products in poor farmland and difficult conditions), 2) review our consumption itself to utilize limited food resources effectively without waste.

In addition, in order to establish strong agriculture, forestry, and fisheries that are able to coexistence with conservation of the global environment, it is important to dramatically enhance sustainability by using the biological function of nature to the utmost, as well as to dramatically increase adaptability for the rapid climate change.

Therefore, WG5 set the following "Target" and "Concept" in each of the three candidates, and will hold discussions with regard to the possibility of realization of these MS goal candidates. In the discussion, Ethical, Legal, and Social Issues (ELSI) perspectives will be considered.

WG5：Innovation for future agriculture –satisfying both food production and environmental conservation

(1) Overcome constraints to water, fertilizers, and other resources by fully utilizing the biological functions of nature by 2050

[Target]

By 2030, the technology to design specific crops in cyberspace will be developed. In addition, a pioneering case of the control technology of nitrogen and phosphorus circulatory systems regulated by soil microorganisms, and of novel pest control technology will also be developed.

[Concept]

In order to achieve a sustainable increase in food production while responding to climate change that is expected in the future, it is necessary to remarkably improve the environmental adaptability of agricultural products.

In order to maintain the agriculture, forestry and fisheries industries, it is also essential to drastically reduce the dependence on water, chemical fertilizers and agricultural chemicals, to prevent adverse effects on the global environment, striving for conservation of biodiversity.

To do so, It is necessary to incorporate genetic material from resilient wild species that are adapted to poor soil and severe environments, in order to generate high-performance crops with excellent environmental adaptability.

Utilizing the useful microorganisms in the soil, etc. (atmospheric nitrogen fixing bacteria, N_2O suppression bacteria, etc.) and useful insects to the utmost will also greatly reduce the dependence on chemical fertilizers and agricultural chemicals, which will realize sustainable agriculture, forestry and fisheries industries considering the conservation of biodiversity as well. Accordingly, we will promote the necessary research and development based on the following concepts.

- Develop super-crops that adapt any environment (AI designed breeding)
- Total control of soil microbial environments, aiming for zero chemical fertilizers
- Total control of pests, aiming for zero agrochemicals

(2) Developing solutions to eliminate food loss and waste and promote rational, health-, and environment-conscious food consumption by 2050

[Target]

By 2030, an AI-supply chain in the food field, a solution prototype that promotes rational, and health- and environment-conscious consumer behaviors will be established.

[Concept]

Along with increasing food supply, it is important to effectively utilize produced food without loss and waste, which will also require us to reconsider consumer behavior.

While we are currently facing social problems, such as the waste of large amount of food, and the increase in obesity and lifestyle-related diseases which are mainly occurring in developed countries, the starvation problem has not yet been solved. It is preferable to develop new solutions which will reduce food loss and waste, and reliably deliver the necessary amount of food to the people who require it.

If the food supply-demand mismatch can be resolved, the loss and waste of food generated in the supply chain and food residues from households will be reduced. In addition, if we can offer a system that can effectively recycle the finally generated residues as food resources, loss and waste can almost be eliminated. For this reason, we will promote the necessary research and development according to the following concepts.

- Establish “Zero-food-loss and waste” / an AI supply chain by driving driven by distribution, quality and personal information

- Development of AI which expands the capability of excellent laborers
- Provide solutions to reduce food loss, waste and residues in households and communities

(3) Establishing a Robust Agricultural, Forestry and Fisheries System Which Can Adapt to Sudden Weather Changes by 2040

[Target]

By 2030, a prototype of the AI cultivation system that unified the information of crop growth from several kinds of sensors and the weather forecast will be developed and the practicability of uninterrupted operation will be verified.

[Concept]

Along with the progression of global warming, unprecedented weather events are occurring more frequently. In order to ensure stable production of food in the future, it is necessary to establish a robust agriculture, forestry and fisheries system which can adapt to sudden weather changes.

Production of food by those engaged in the applicable industries is not enough, based on the experience and intuition gained over many years. It is necessary to implement flexible actions utilizing high precision sensors which quickly sense the signs that cannot be detected by people, so that the people engaged in agriculture, forestry and fisheries can be prepared for sudden changes in the weather (cold weather damage, abnormally high temperatures, typhoons, etc.) and the occurrence of pest insects, etc., analysis technology for the huge agricultural data and AI robots. For this reason, we will promote the necessary research and development on the following concepts.

- Development of innovative sensing technologies which enable high-precision agriculture, forestry and fishery industries, beyond the five senses of excellent laborers
- Development of AI which expands the capability of excellent laborers
- Creation of intelligent farms, which operate 24 hours / 365 days a year exceeding the techniques of excellent laborers

3. Why Now?

With the progression of global warming, abnormal weather is occurring more frequently worldwide, and the future food supply is likely to become more unstable.

In the Representative Concentration Pathway (RCP) scenarios published by the International Panel on Climate Change, it is envisaged that if there is no control on the emission of greenhouse gases (RCP8.5), then by the year 2100 the average temperature on land will increase by 2.6 to 4.8°C (Figure 3). If this situation is realized, the harvests in the grain belts of the world are likely to be reduced greatly and become unstable.

Also, as a result of the spread of irrigation farming the demand for water is dramatically increasing (Figure 4). Depletion of groundwater, reduction of rainfall due to abnormal weather, frequent torrential rain damage, etc., are already being experienced throughout the world.

In Japan it is also forecast that the frequency of occurrence of extreme torrential rain in the future will more than double (global warming forecast information from the Japan Meteorological Agency based on the RCP8.5 case), and severe damage to agricultural produce is anticipated.

As the food supply risks increase in the future, in terms of demand it is estimated that the world population in the year 2050 will increase by a factor of 1.3 (relative to 2010). With the increase in demand for grain as food for livestock in medium income countries, it is anticipated that the demand for food will greatly increase by a factor of 1.7. It is anticipated that there could be a serious shortage of food worldwide in 30 years time (Figure 5).

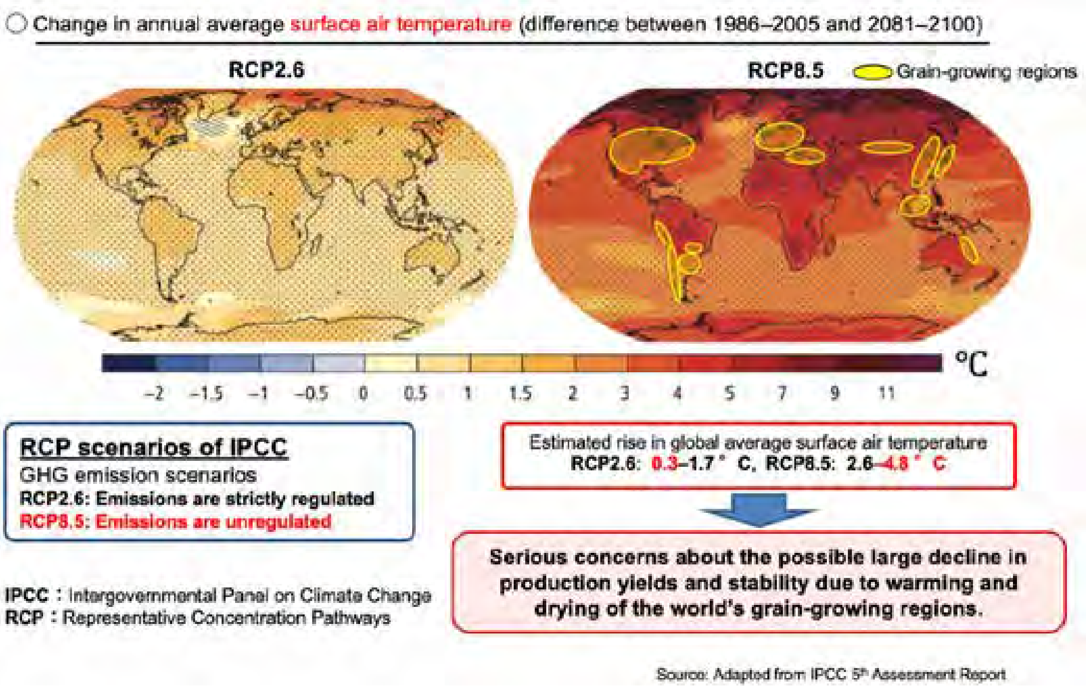

Figure 3　Climate change risks from continued global warming

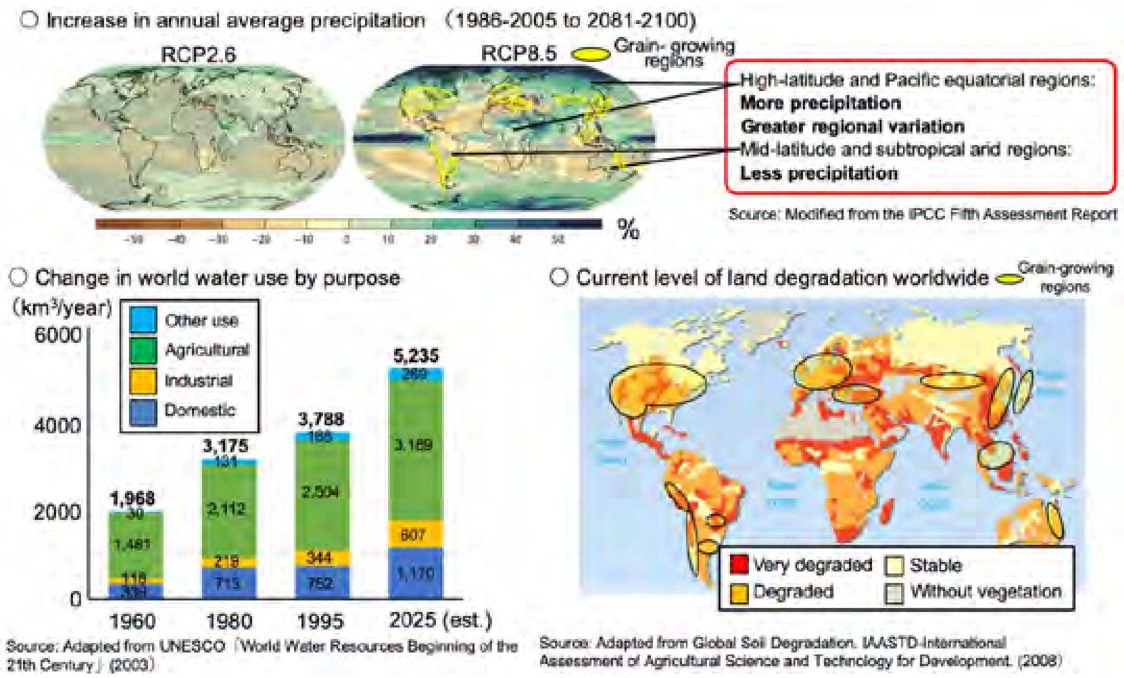

Figure 4　Impact of water resource limits on agricultural production

Japan has a low degree of self-sufficiency in food (self-sufficiency in food was 38% in 2018), and at present Japan depends on overseas agricultural land equivalent to 2.4 times the area of Japanese agricultural land (about 4.5 million ha, Figure 6), so it is envisaged that the future increase in world demand for food will have a serious effect on the Japanese food supply.

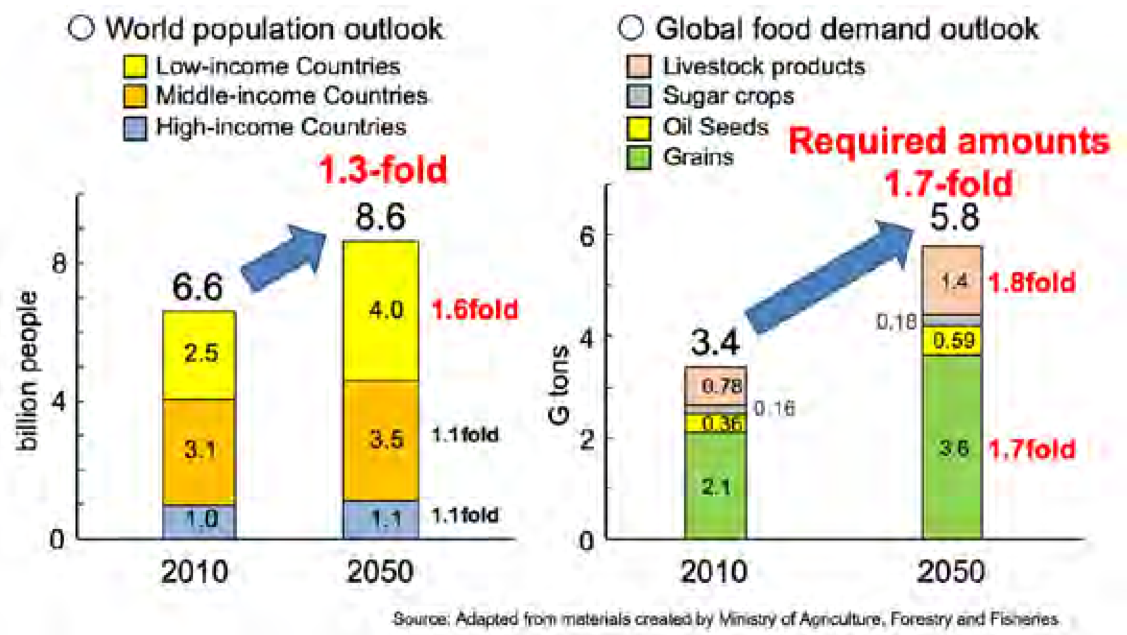

Figure 5 Outlook for global food demand in 2050

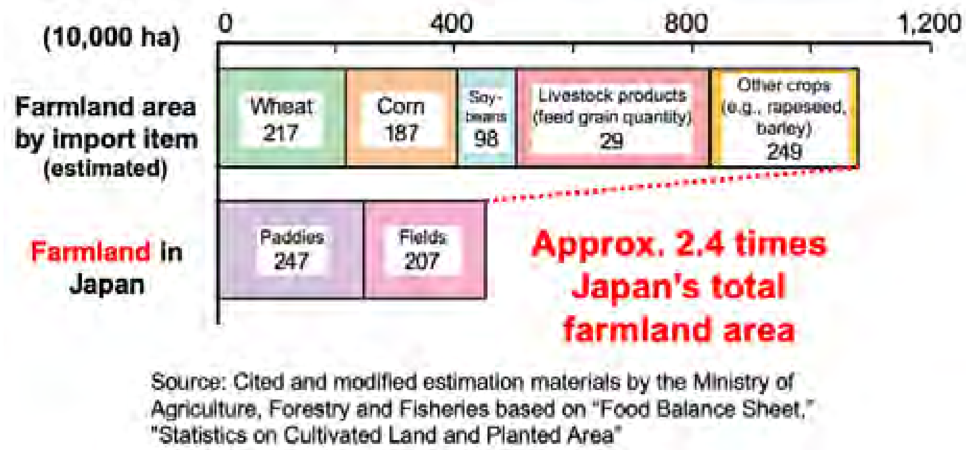

Figure 6 Reliance on overseas farmland

On the other hand, considering the actual status of food consumption, every year in Japan 6.3 million tons of food is disposed of as waste, and there are many issues associated with food such as obesity and diseases related to adult lifestyle habits.

Also, regarding reduction in greenhouse gas emissions that are responsible for global warming, it is said that 1/4 of the total worldwide emissions of greenhouse gases including N_2O, methane, originates from agriculture, forestry, and other land use (IPCC, 2014).

In the future, it will be necessary to enhance the biological function of the agriculture, forestry, and fishery production, such as absorbing CO_2 and converting it into useful organic matter effectively. It will also be necessary to rapidly establish agriculture, forestry, and fishery production systems that do not generate N_2O or methane in order to contribute towards reduction in greenhouse gas emissions. Also, it is considered that it will be important to increase the function of forests for water recharging, ensuring good quality water resources, preventing floods.

Against this background, the United Nations Sustainable Development Goals (SDGs, Table 1) promote the importance of:

(1) Conserving the ecosystem, increasing the capacity to adapt to climate fluctuations, and promoting sustainable agriculture (Goal 2)

(2) Expanding afforestation on a global scale, and promoting conservation of natural ecosystems, including conservation of biodiversity (Goal 15)

(3) Conserving oceans and ocean resources, and utilizing them in a sustainable manner (Goal 14)

(4) Reducing food waste and food losses, and ensuring sustainable forms of production and consumption (Goal 12), and today international cooperative activities are starting.

In view of the above, there is an urgent necessity to bring together the wisdom of researchers and businesspeople throughout the world to promote challenging research and development based on the three unified tasks of "establishing robust agricultural, forestry, and fisheries systems that can adapt to rapid climate change", "coexistence of both utilization of biodiversity and conservation of the environment", and "elimination of food loss", in order to achieve sustainable increased production in food in accordance with the rate of increase in the world population in the future (Figure 7).

Therefore it is indispensable that Japan, which has strengths in the IoT and robotics fields and in biotechnology, should set ambitious MS goals in these three fields and undertake challenging research and development initiatives, in order to deal with the problems of stable supply of food in the world and global warming, as well as to ensure food security in Japan in the future.

Table 1 Points regarding SDGs Relating to Food, and the Agriculture, Forestry, and Fishery Industries

2	**End hunger, achieve food security and improved nutrition, and promote sustainable agriculture** ・Ending hunger, ensuring safe and nutritious food, etc. ・Improving productivity and production quantity, conserving ecosystems, improving the power of adaptation to climate change, etc., sustainable food production systems, resilient agriculture ・Maintaining the genetic diversity of seeds, etc., expanding investment in agricultural village infrastructure, agricultural research, and dissemination services, etc.
6	**Ensure sustainable use and sustainable management of water and sanitation for all** ・Access to safe and low cost drinking water ・Major improvement in efficiency of use of water in all sectors, and sustainable acquisition and supply of fresh wate ・Protection and restoration of aquatic systems such as forests, rivers, lakes, etc.
12	**Ensure sustainable consumption and production patterns** ・Sustainable management and efficient use of natural resources Reduction of food waste at the retail and consumer level by half, reduction of food losses in production and in the supply chain, etc.
13	**Take urgent action to combat climate change and its impacts** ・Strengthen resilience and adaptability to climate-related disasters and natural disasters ・Climate change mitigation, adaptation, impact reduction, early warning, etc.
14	**Conserve and sustainably use the oceans, seas and marine resources for sustainable development** ・Major prevention and reduction in ocean pollution ・Restoration of ocean and coastal ecosystems, minimization of the effect of ocean acidification ・Effective regulation of fishing, implementation of scientific management plans, etc.
15	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss** ・Conservation, restoration, and sustainable use of terrestrial ecosystems and inland freshwater aquatic ecosystems, such as forests, wetlands, etc. ・Major increase in new afforestation and reforestation in the world as a whole, and conservation of natural ecosystems including biodiversity ・Restoration of soil such as land affected by desertification, etc., and prevention of introduction of invasive alien species, etc.

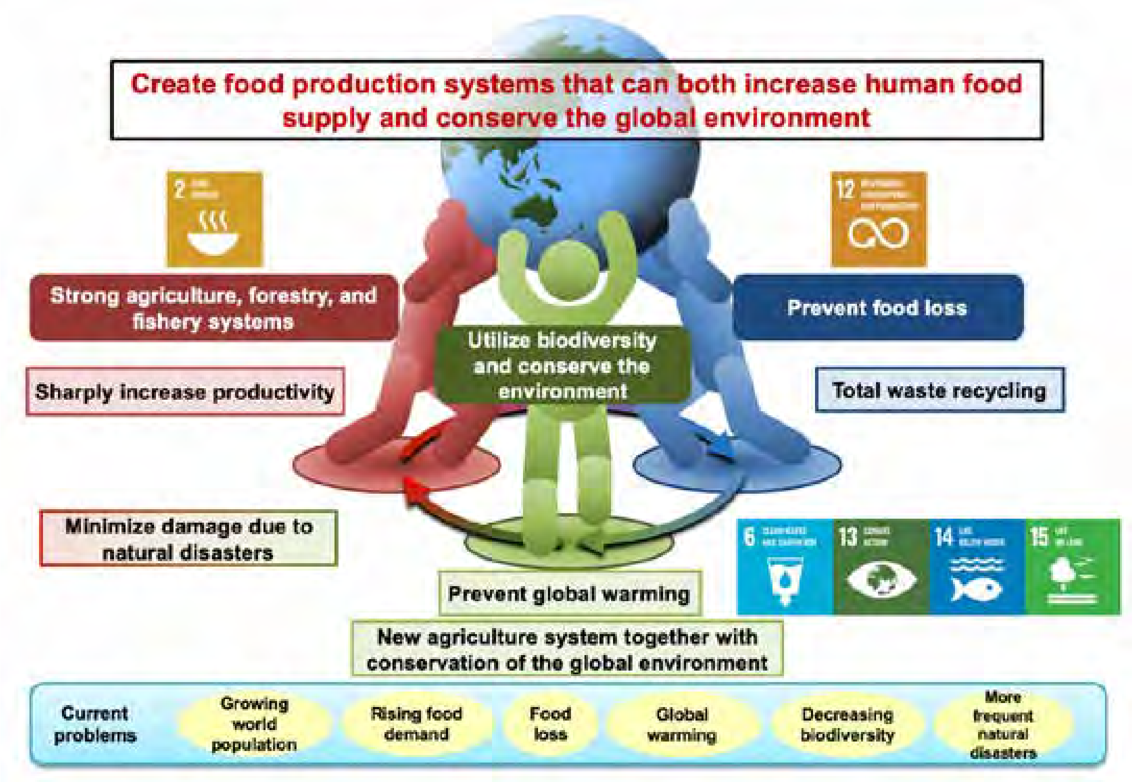

Figure 7　Necessary direction for Moonshot Research work

4. Changes in industry and society

Establishing new agriculture, forestry, and fishery production systems together with conservation of the global environment will enable a sustainable increase in production of food in accordance with the increase in world population. These systems can contribute to stabilizing the social economy, overcoming hunger and poverty, and disseminating healthy food consumption habits, etc.

Also in Japan it is expected that establishing new production systems will result in dissemination of agriculture, forestry, and fishery industries that are highly adaptable to abnormal weather, etc., and increased self-sufficiency in food, as well as contributing to the creation of innovative services that can expand globally and to the development of the economy.

<MS Goal candidate 1>

Overcome constraints to water, fertilizers, and other resources by fully utilizing the biological functions of nature by 2050

II. STATISTICAL ANALYSIS

1. Structure of MS Goal

There are concerns over the decline in farmlands due to increased global warming. To increase food production in accordance with the rate of increase of the world population, it is necessary to expand the use of barren and unused areas as farmland and dramatically improve crop yields. Therefore, it is necessary to develop crops with high environmental adaptability that can be cultivated and maintained in poor farmland and any conditions.

Large amounts of chemical fertilizers are used in the agricultural fields. Ingredients in fertilizers include phosphates and potassium, for which the reserves of mineral resources are limited and will become eventually depleted. However, Japanese farmlands have accumulated large amounts of phosphoric acid components over many years of fertilizer application, although they have not been effectively used by crops.

Excessive application of nitrogen fertilizers causes river and water pollution. Furthermore, enormous energy is required to produce nitrogen fertilizer using nitrogen from the atmosphere as raw material. In addition, greenhouse gases such as nitrous oxide, resulting from the use of nitrogen fertilizers are generated in large quantities in upland fields and during the breeding of livestock. These emissions cause global warming. To overcome these problems, it is necessary to reduce the use and increase the effectiveness of chemical fertilizers using microorganisms and livestock excrement, which can control the generation of greenhouse gases.

Moreover, due to the effects of global warming and the globalization of the food distribution chain, there has been an increase in the expansion of pest-damaged areas and the occurrence of sudden pest outbreaks worldwide, which significantly interferes with stable food production. Large inputs of chemical pesticides not only damage the natural biodiversity including useful insects such as natural enemies of pests, but have also led to production losses due to the development of resistance to specific chemical pesticides.

(1) Development of crops with excellent environmental adaptability

a) Collection and analysis of genetic resources and information

To develop crops with excellent environmental adaptability, it is necessary to actively use genetic resources to incorporate characteristics of wild relatives to crop species, such as drought and salt tolerance, into the cultivated species.

Since the start of the Gene Bank Project in 1965, Japan has collected genetic resources of approximately 200,000 crop accessions and wild relatives from Japan and abroad (FAO, 2011). However, work on decoding the genomic information and specific work on useful genes in these wild relatives is delayed.

Furthermore, it is expected that related wild type species have many valuable genes that have been lost through the process of domestication, masking traits such as disease resistance and cold tolerance, and high yields. By using next-generation sequencing (NGS), which has emerged in recent years, we may be able to decode the genes related to these characteristics and markedly increase the environmental adaptability of crops.

b) Advancement and efficacy of breeding technology

Crop breeding techniques are based on crossing and phenotypic selection, and it is therefore a laborious time-consuming process. Recently, progress has been made in MAS (marker-assisted selection) technology that selects genes based on the genomic information rather than on the phenotype, and selects materials with the most desirable combination of genes (genomic selection). Based on these technologies, the development of new crops that involve multiple promising genes for target phenotypes are underway (Crossa et al., 2017). However, it is difficult to improve complex traits such as grain yield, resistances to drought, salinity and waterlogging that are controlled by a large number of genes. For these reasons, there is an urgent need to develop novel technologies to overcome these limitations.

Regarding genomic information, which is the blueprint of life, there have been advancements in the decoding of genomes in major crops due to dramatic improvements in computer processing and DNA sequencing technology (Michael and VanBuren, 2015). It has become possible simultaneously to obtain and link together information on crop phenotypes, genotypes, and cultivation environment; therefore, efforts to develop technologies to actively use such information to breed plants are being conducted. However, there are still challenges in accumulating, standardizing, and increasing the accuracy of big data, including high-accuracy data in the fields to use them for breeding.

In 2012, a highly versatile artificial restriction enzyme was discovered, which led to the development of a more precise, efficient, and adaptable genome editing technology that can introduce mutations on the target genes (Vats et al., 2019). Research on “synthetic biology”, which creates artificial life by reconstructing life components based on the knowledge of life systems accumulated by these molecular biology techniques, started a few decades ago and is being widely used at present (Ostrov et al., 2019).

Given this background, a revolutionary concept regarding breeding has recently been proposed, whereby the idea of crop breeding has fundamentally changed from “selecting” to “creating”(Eshed and Lippman, 2019). It is expected to develop groundbreaking crops in a very short period of time based on this concept through the accumulation and linkage of these technical elements and the active use of AI.

However, the challenges for such technological development include the consolidation of large data on breeding, as mentioned previously, and the lack of a methodology for quickly creating crops. Such technology can be used to accurately insert mutations in hundreds of sites at once and apply artificial genome design to crops and agricultural products, which have otherwise only been successful in single-cell organisms such as yeast.

(2) Techniques for the reduction of the use of chemical fertilizers and increase of its effectiveness

Agricultural crop production is severely dependent on the input of fertilizers containing nitrogen, phosphorus, and potassium. The use of large quantities of fertilizer has become especially striking in developed countries since the "Green Revolution". However, based on estimated mineral reserves, the number of minable years for phosphorus and potassium (financial reserves) has been calculated as 125 to 260 years and 310 years, respectively. For this reason, unless major changes are introduced into the fertilizer-dependent crop production system, depletion of raw materials used to obtain fertilizers will lead to the failure of the food production system.

Phosphate fertilizers are extremely ineffective due to poor solubility caused by the soil fixation of phosphorus and only 1% of the total inorganic and organic phosphorus in the soil is absorbed by plants in Japan(Zhu et al., 2018). Excessive input of nitrogen and phosphorus to farmland also causes the pollution of rivers and groundwater.

As a result of these conditions, the large-scale reduction and optimization of chemical fertilizer usage are critical issues. To maintain agricultural productivity and prevent global warming, agriculture must move away from traditional crop production systems based on large quantities of chemical fertilizer input and create progressive innovation.

To achieve this goal, agricultural byproducts (organic matter) and livestock waste must be recirculated as sources of nutrients for plants and the effectiveness of nitrogen, phosphorus, and potassium fertilizer must be improved. As microbes in the soil are closely linked to the loss, fixation, and storage of nitrogen and phosphorus in agricultural production, a technology for managing the soil microbial environment is key for solving the current problems.

a) Improving fertilizer (nitrogen, phosphorus, and potassium) usage effectiveness

Measures to reduce phosphorus fertilizer usage has not progressed in Japan.

With Regard to nitrogen, research aimed at increasing the effectiveness of nitrogen fixation in legumes has been conducted. However, in many cases the effectiveness of the fertilization has been lower than expected. Although attempts have been made to introduce symbiotic genes identified in legumes to non-legume plants to confer nitrogen-fixation properties (Rogers and Oldroyd, 2014), so far these efforts have not been successful. If the optimization of the plant and microbe symbiosis could be used to achieve effective nitrogen fixation, it will be possible to develop ground-breaking technologies for plant-based biological nitrogen fixation in non-legumes. In addition, livestock waste, which is a contributor to environmental pollution, must be more proactively used as a fertilizer.

b) Improving symbiotic phosphorus absorption in plants

The depletion of phosphorus mining reserves and the decline in the quality of the extracted materials are expected to occur, and will result in unavoidable surging prices for chemical phosphorus fertilizers. In the future, this may lead to higher prices for agricultural crops as well. In addition, as soil clings to phosphorus and reduces solubility, phosphorus fertilizers are extremely ineffective. If a technology that enables crop production to effectively use phosphorus fixed in the soil is developed, crop production without the use of phosphorus fertilizers would be possible.

Through symbiosis with plants, mycorrhizal fungi absorb phosphorus in the soil and provide it to their hosts. As this fungus can form symbiotic relationships with 80% of the terrestrial plants, research and development on mycorrhizal fungi for effective usage of soil-bound phosphorus is underway (Zhu et al., 2018). However, the effectiveness of fungal inoculation to reduce phosphorus fertilizer usage is inconsistent and these efforts have not been able to promote a reduction in phosphorus fertilization reduction. In the future, if detailed operating mechanisms and improvement techniques for mycorrhizal fungi are established, the functionality of the fungus itself could be modified, achieving benefits such as augmented phosphorus absorption.

The world's first artificial cultivation system for mycorrhizal fungi was built this year (Kameoka et al., 2019). A single-line selection system for mycorrhizal fungi using moss was also reported. The utilization of these base systems is likely to make major contributions to the technological developments required to reduce fertilizer usage.

(3) Greenhouse gas control technology

Global greenhouse gas emissions reached 49 billion tons (CO_2 conversion) as of 2010 and the agricultural, forestry, and other land use industries accounted for 1/4 of the total (Figure 8, (IPCC, 2014)).

Methane and N_2O produced by soil microbes constitute an especially large proportion of the greenhouse gases that originate from agriculture, of these two, N_2O is formed and emitted from nitrogen fertilizer. As the global warming potential of methane and N_2O are 28- and 265- times greater, respectively, than that of carbon dioxide, these gases are major contributors to global warming. For this reason, reducing the emissions of these gases is an urgent requirement for mitigating greenhouse effects in the agricultural sector. Establishing a method for the accurate evaluation of forests, accumulated organic matter in the soil, seaweed, and other materials that absorb CO_2, and strengthening the measures for promoting this absorption are also important issues.

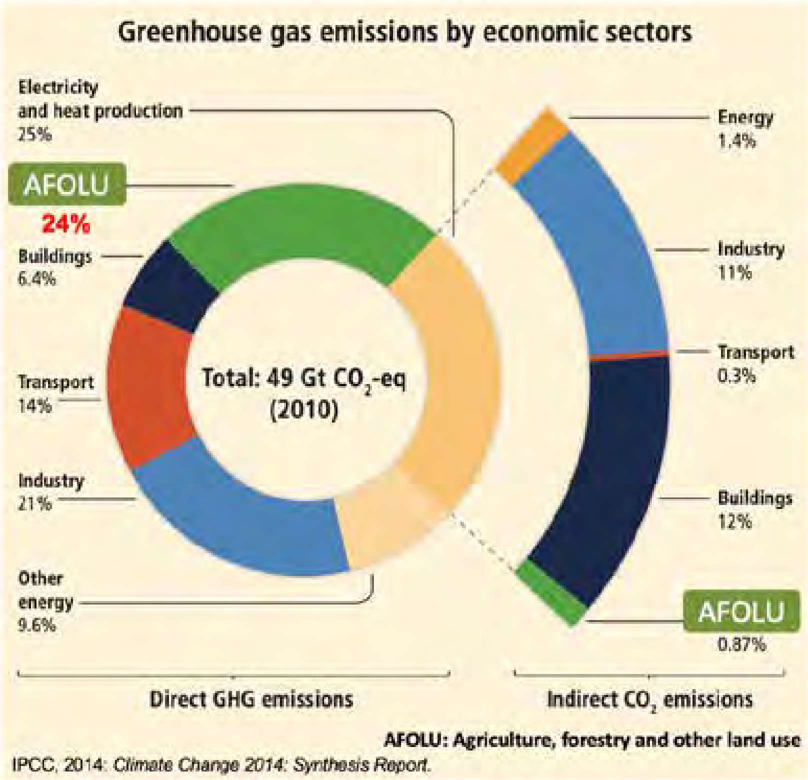

Figure 8 Total anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2- equivalent per year, $GtCO_2$-eq/yr) from economic sectors in 2010.

a) Methane

Overall, 11% of world methane emissions are from rice paddies (IPCC, 2014). As methane is produced in anaerobic environments when methanogic microbial communities metabolize organic materials, methane reduction methods based on modified rice cultivation practices are currently being developed and implemented (Malyan et al., 2016).

However, as there is currently limited information about the mechanisms for metabolic organic material and its stable accumulation, as well as the relation between microbial communities and the rice plant, the effectiveness of these methods is limited.

In the future, if a control technology is developed based on detailed analyses of the metabolizing processes of organic material in the soil and their relation with rice plants and soil microbes, including the ecology of methanogen and methane-oxidizing bacteria, it will cause a consistent and effective reduction in methane emissions on agricultural sites (Figure 9).

b) N_2O

Of the total man-made N_2O worldwide, approximately 59% is produced by agriculture (IPCC, 2014).

N_2O is produced from excess nitrogen fertilizer by nitrifying and denitrifying bacteria and is released into the atmosphere. For this reason, there are attempts to reduce its emission by improving fertilization methods and applying coated fertilizers.

However, the reduction effects vary depending on the characteristics of the soil and there are no definitive effects yet. In addition, although the N_2O reducing effect on artificial chemicals has been investigated, there is currently limited information about the ecology and nitrogen metabolizing enzymes of the targeted nitrifying and denitrifying bacteria, the nitrogen utilization efficacy of plants, and the dynamic state of inorganic nitrogen, thus, the effectiveness of these materials is limited.

To drastically reduce the generation of N_2O, future efforts will be needed to obtain fundamental knowledge such as the microstructure of the soil, the diversity of the target microbes, their ecology and interactions in the soil, and analytical methods for microbial function in the soil nitrogen cycle. If a control technology is developed based on this information, this will cause a consistent and effective reduction of N_2O emissions on agricultural sites (Figure 9).

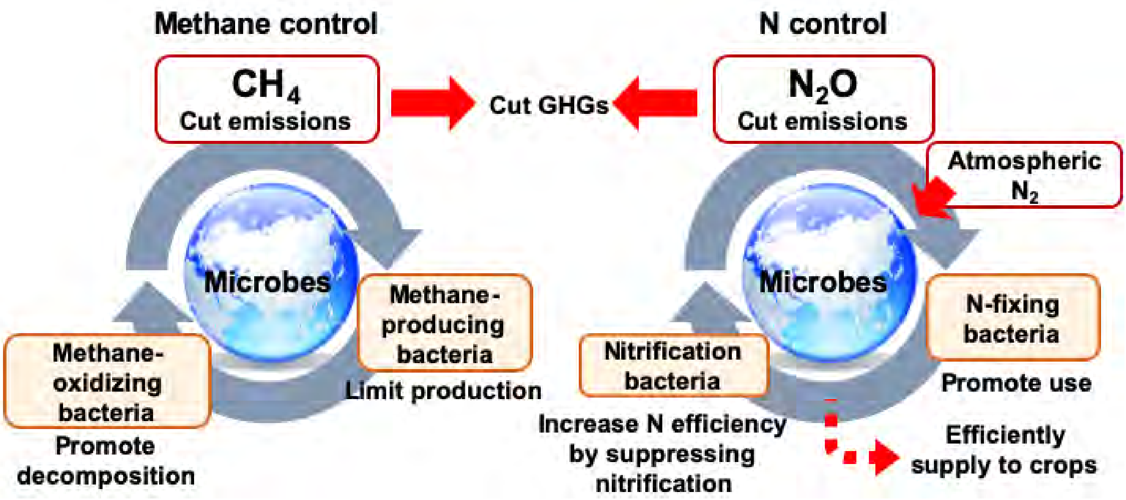

Figure 9 Overview of the generation of nitric oxide and methane by soil microbes

(4) Increasing accuracy of pest control technology

Currently, pest control technology focuses on chemical pesticides that are effective if used appropriately, but become ineffective when pests develop resistance to them. Such problems have been occurring on a global scale (APRD, 2019). The development of pesticide resistance has been spreading every year among various pests, with an endless race taking place between pesticide development and the development of resistance in pests (APRD, 2019; Sparks and Nauen, 2015). Some insect pests have already developed multiple types of resistance, making them increasingly difficult to control. Moreover, there have been cases in which chemical pesticides reduced biodiversity, due to their adverse effects on insects and organisms other than the targets of the pesticides.

To solve these problems, it is important to effectively undertake pest control measures by predicting the occurrence of pests in advance, and by quickly and accurately identifying the pest species that have emerged. Moreover, in the context of pest control, it is crucial to depart from the endless race between pesticide development and the emergence of resistance in pests. A shift towards new control methods that prevent the development of resistance in pests is essential. Hence, the application of new control methods is imperative. These methods could include strategies that make use of the natural enemies of pest, or drive away or harm the pests by physical forces such as sound or light, or suppress the reproduction of pests.

a) Pest diagnosis and forecasting technology

The method to identify pest species and determine whether they will cause economic damage, to assess whether a control is necessary or not, is called "pest forecasting." Conventionally, well-trained experts have made pest forecasting decisions. In recent years, the development of technologies using AI and drones, and the creation of an application to automatically identify pest species and their quantities based on photographic images are being studied. However, the research is still preliminary. Combining visual information with other cues such as volatile substances and vibration, highly precise pest diagnosis methods may be developed. If we could instantly distinguish between pest species and non-pests, and then automatically count the number of pests in the field, it would enable more effective forecasting and early control of pest. These new technologies would enable a control that precisely targets pests while protecting the non-pest species, resulting in increased biodiversity.

In addition, predicting the number of pest insects is crucial to determine whether the control is necessary or not. A new technology currently under development aims at predicting the quantity of pest occurrence and the resultant damage, based on the relation between weather factors and pest reproduction. In the future, effective and precise pest control will be possible by improving the precision of weather forecasting and using AI and other technologies to automatically predict the number of pest occurrences and damages.

b) Control technology that does not cause pests to develop resistance

To date, various chemical pesticides have been produced. However, pests are known to develop resistance to some chemical pesticides. A considerable amount of time and money (nine years on average; $152–$256 million) is required to develop a new pesticide (Sparling, 2016). Moreover, the number of new products has been decreasing over the recent years. In the future, sustainable agricultural production will be possible if pest control technologies based on a newer concept is established: a technology that does not depend on chemical pesticides and prevents the development of resistance in pests.

In recent years, the development and practical use of natural enemies of pests has been gathering attention in various parts of the world. Several methods that involve multiplying and releasing natural enemies of pests have proven to be useful in closed-type cultivation environments, such as greenhouses. In contrasts, several attempts have been made to protect and use native, natural enemies in open-field cultivation (Shields et al., 2019). So far, there have been many cases in which specific natural enemies have been used for controlling specific pest insects. However, well-planned combinations of multiple natural enemies will be a more effective strategy to control a wide range of pest species. In addition, the breeding of natural enemies of pests (a technology to select useful natural enemies) that are not able to fly and leave the fields, has been undertaken. One such example is the "flightless strain of the ladybird beetle" (Lirakis and Magalhães, 2019; Seko et al., 2008). In the future, the development of natural enemies of pests that can be used in open environments is expected to facilitate a more effective pest control strategy. Notably, this will involve the artificial enhancement of functions in natural enemy insects using technologies such as genomic editing.

Physical pest control methods, using sound and light to gather, drive away, or kill insect pests, are promising. In recent years, studies have demonstrated the pesticidal effects of lasers and lights with specific wavelengths (Hori et al., 2014; Shibuya et al., 2018). Another technology using ultrasound to prevent insect intrusion has been effectively used in case of certain species (Nakano, 2012). In addition, a technology that involves casting a light of certain wavelengths to suppress pest behavior has been developed and partially put to practical use. In the future, pest control strategies compatible with a wide variety of crops and cultivation conditions will be possible by expanding the scope of such technologies beyond the original intended species.

c) Control technology to manipulate the population growth of pests

Technologies that manipulate insect proliferation or exterminate them have been established and put to practical use for several species of intrusive insect pests. These technologies involve the release of insects that have been rendered infertile by exposing them to radiation. However, the production of infertile insects conventionally requires large-scale irradiation facilities, and a rigorous management of the irradiation sources. In addition, this method is unable to regulate the impact of irradiation on traits other than fertility. Methods for inducing infertility including genetic modification, genomic editing technology, or the use of symbiotic bacteria such as *Wolbachia* (a genus of symbiotic microorganisms that infect insects) are still in the early stages of research (Zheng et al., 2019) but have progressed dramatically in recent years, with the potential to become effective methods in the near future.

2. Science and Technology Map

Studies on the interaction between plants and soil microorganisms (Figure 10, gray dots) and symbiosis (green dots) are ongoing, but started to increase from 2012. There has been a slight increase in research on soil microorganisms and greenhouse gases since 2015, but the number of studies is still small (yellow dots). Studies on genome editing in microorganisms have been increasing since 2013 (orange dots), but when the studies are limited to soil microorganisms, the number is extremely small (11 cases, data not shown). Therefore, studies on the design and modification of soil microorganisms could be regarded as a future field of research.

However, the number of studies on genome editing in plants has increased rapidly since 2013 (blue dots). This coincides with the time when CRISPR/Cas9 began to be applied to plants. Research results are expected on topics including the development of basic technology for genome editing and crop creation using genome breeding technology. In contrast, there are still few studies on breeding using AI (39 cases, light blue), which shows that this research is in its infancy. However, the number of cases began to increase in 2019 and research in this field is expected to increase rapidly in the future.

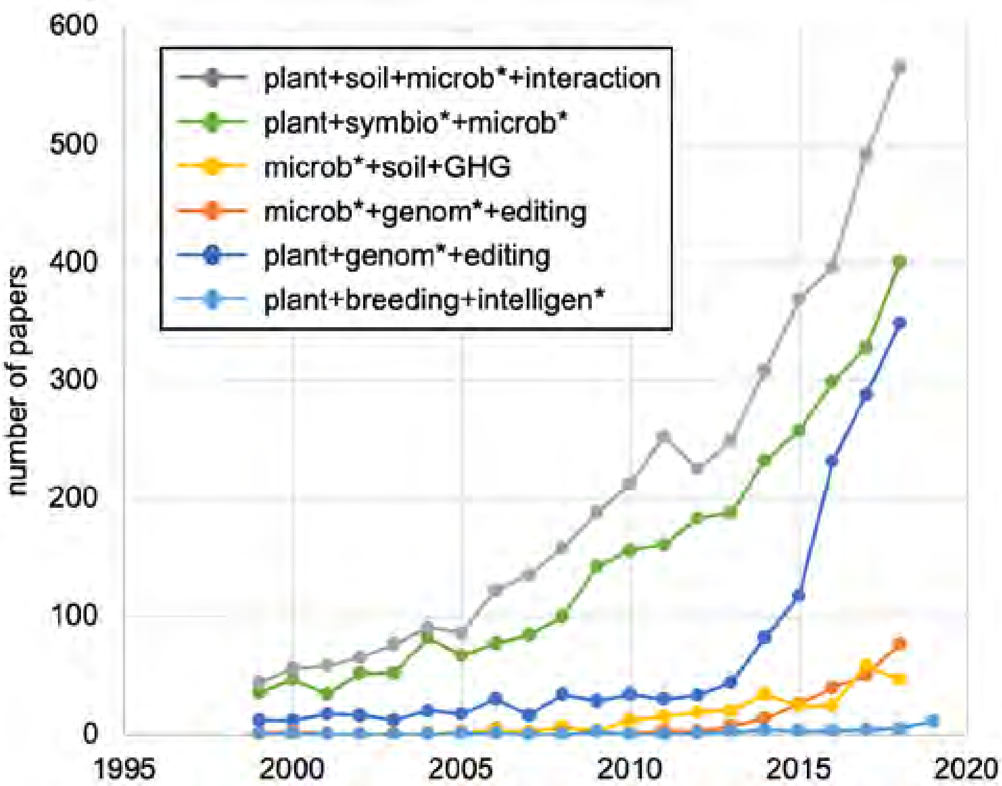

Figure 10 Research trends on breeding and soil microorganisms in Japan and overseas from 1999 to 2019 (Clarivate Analytics, Web of Science)

An overview of the research trends on the development of pest control methods, shows that the two predominant fields with the largest number of papers to date are chemical control (chemical pesticides) and biological control (use of natural enemies of pests) (Figure 11-A). The next largest fields of research are related to physical control, cultural control, resistant varieties, symbiotic microorganisms, and sterile insect techniques. Of these, the two areas in which the number of research cases has increased significantly over the past five years are the use of symbiotic microorganisms and the release of infertile insects (Figure 11-B, purple and light blue dots). However, the number of studies on pest control using genome editing has increased rapidly in the last three years and research using drones and AI is also starting to increase. Research in these fields is expected to increase further in the future (Figure 11-C).

In the field of life sciences, omics analysis at the single cell level has become possible over the past few years, and imaging technology has made significant progress. Furthermore, the accuracy of genome editing technology has improved, and it is being developed for application in medical and food industries. Information and communication technologies (ICTs) such as measurement technology and AI machine learning are steadily making inroads into life sciences through automation and scale-up. In addition, understanding of life phenomena is progressing through a new "data-driven" approach to discover laws from a large number of phenomena occurring in life. On the contrary, with the progress of AI, genome editing, synthetic biology, and so on, ELSI are posited as important challenges in the promotion of science and technology (R&D overview report, integrated version 2019).

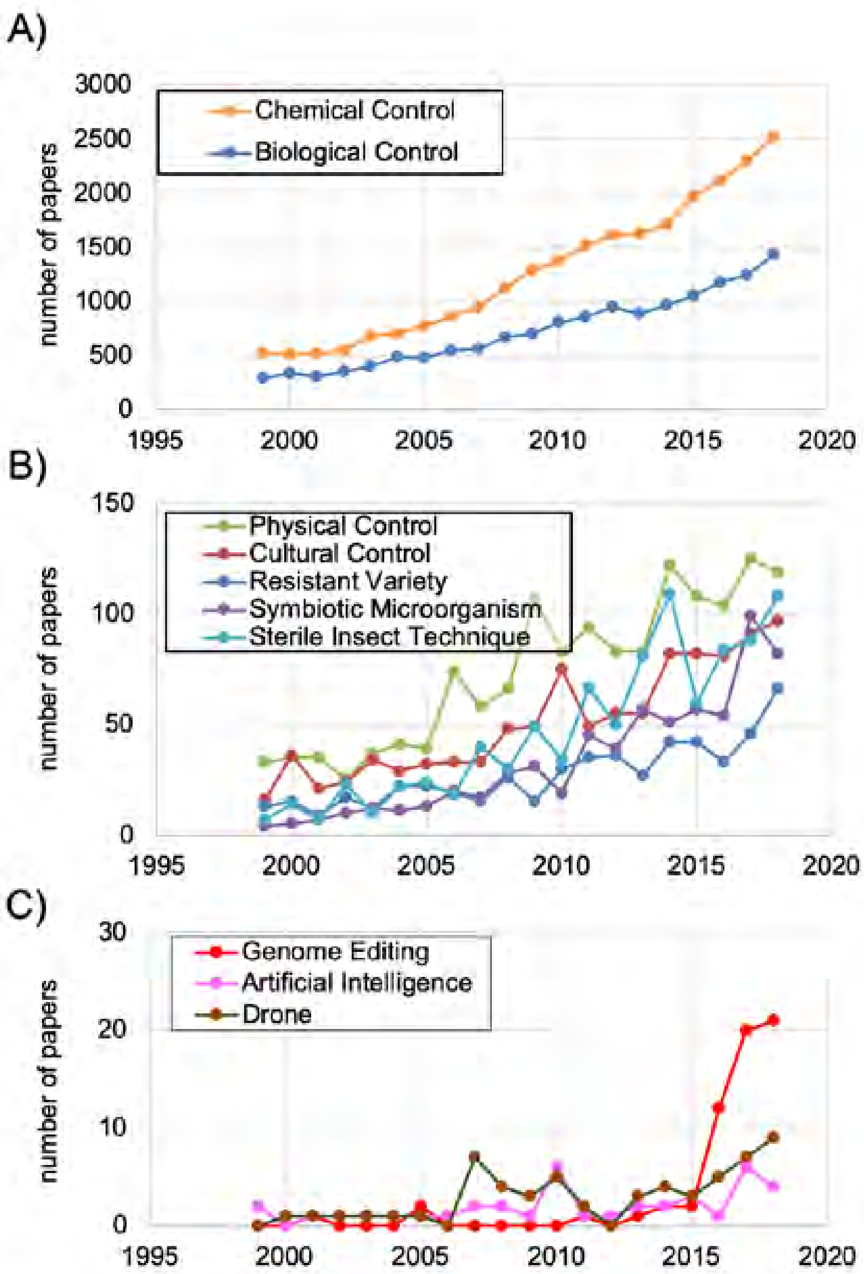

Figure 11 Research trends on pest control in Japan and overseas from 1999 to 2018 (Clarivate Analytics, Web of Science)

III. SCENARIO FOR REALIZATION

By 2050, to overcome constraints of resources such as water and fertilizer, to achieve the ultimate reduction of environmental burden, and to maintain sustainable agricultural production simultaneously, the following are important. 1) Quick creation of super crops with high environmental adaptability with unprecedented resilience, 2) Utilization of soil microbial environment that is closely related to fertilizer use effectiveness and global warming, and creation of technology that controls the soil microbial environment, and 3) New pest control system that makes full use of environment-friendly biotechnology. In order to implement these technologies, the R&D must be addressed strategically, collaborating with industry, academia and government officials. Domestic and international discussion about ELSI must also be considered.

1. Realization of Goals

(1) Development of super crops with high environmental adaptability (AI-designed breeding)

The aim is to elucidate all gene functions of crops and based on the results establish a rapid and unrestrictive crop development technology to create innovative crops able to maintain productivity in sterile environments, even with zero fertilizers and pesticides. Spreading and expanding the super crops with high environmental adaptability will achieve the goal of creating a sustainable food production system at the global level. Therefore, the following research examples are envisioned.

To incorporate the "resilience (such as drought resistance, flooding resistance, salt resistance)" of wild species into the cultivated species, the whole mechanism of these "resilience" will be elucidated by various omics analysis and other advanced techniques that have made great progress in recent years (Figure 12).

Based on the novel concept of fusion of advanced information processing technology and AI with "synthetic biology (creating life artificially)", a revolutionary concept has recently been proposed with respect to breeding, whereby the idea of crop breeding is fundamentally changed from "selection" to "creation". Therefore, the technology to design desired crops in the cyberspace, as well as to create crops that have significantly improved environmental adaptability based on the design will be developed.

In the next ten years, the following research results will be obtained as individual elements: 1) identification of genes involved in "resilience" from wild species, 2) development of the technology to design crops possessing "resilience" in cyberspace, and 3) development of the technology to modify/create genes based on the design. And further, pioneering cases to create crops using above technology will be explored. In the subsequent phase, up to year 2050, such technology will become more sophisticated and universal. In 2050, the anticipated creation of innovative crops able to achieve sufficient productivity in sterile environments, even with zero fertilizers and pesticides, is envisioned.

(2) Aiming for zero chemical fertilizers by completely controlling the soil microbial environment

The aim is to fully elucidate the microbial environment in soil, which is closely involved in the emission of methane and N_2O, and absorption of nitrogen, phosphorus, and other elements into plants in agricultural production. Based on the outcomes of this research, the technology to fully use symbiotic and useful microorganisms in the soil, greatly reducing the dependence on chemical fertilizers and greenhouse gas emissions, will be established (Figure 13). This will create the optimal soil environment for agricultural production and achieve the goal of resolving social problems using zero chemical fertilizers, which will result in a significant reduction of greenhouse gases. Thus, the following R&D examples are envisioned.

Since most of the microorganisms in soil cannot be cultured, it has been difficult to analyze these functions. However, single cell omics analysis and novel microorganism isolation and culture techniques have remarkably developed in recent years. Using these techniques, identification and functional analysis of useful microorganisms that contribute to the efficient use of fertilizers in the soil will be performed.

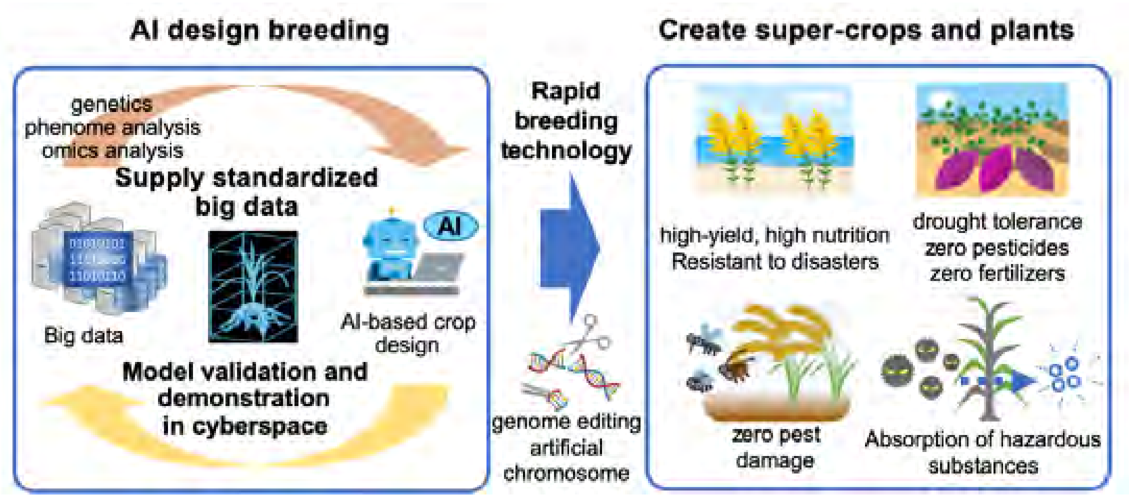

Figure 12 Conceptual diagram of super crop creation technology (AI design breeding) with high environmental adaptability

Furthermore, interactions between soil microorganisms and among soil microorganisms, soil environments, and plants, which form the whole environment around the soil microorganisms, will be comprehensively elucidated using microbiome studies and imaging analysis that have greatly improved in recent years.

Based on the above knowledge, and in collaboration with research obtained by related Moon Shot research programs, technologies to control and use soil microorganisms to drastically reduce the emission of greenhouse gases such as N_2O and methane, maximize the usage effectiveness of nitrogen from the air and nitrogen and phosphorus compounds in the soil, and create robust crops that do not require chemical fertilizers and pesticides will be established.

Microbes, plants, and the soil have evolved and interrelated in terrestrial ecosystems over the past 500 million years and are regarded as “integrated communities of microorganisms, plants, and soil”. The techniques for freely designing and reorganizing these “communities” will be developed by using AI. Furthermore, an artificial soil ecosystem that optimizes crop production without relying on chemical fertilizers will be constructed.

In the next ten years, nitrogen and phosphorus circulatory systems regulated by soil microorganisms will be elucidated, and technology that controls these circulatory systems will be developed utilizing the knowledge. These technological developments are expected to produce pioneering development cases for specific crops under specific environments. In the subsequent phase, R&D for a practical application will be implemented, including optimization and verification contributing to a significant reduction of greenhouse gases and zero chemical fertilizer, as well as the concomitant verification in the field. The optimal soil ecosystem to generate agricultural products suited to various environments will be created by year 2050, thereby enabling zero use of chemical fertilizers and resulting in a drastic reduction of greenhouse gases.

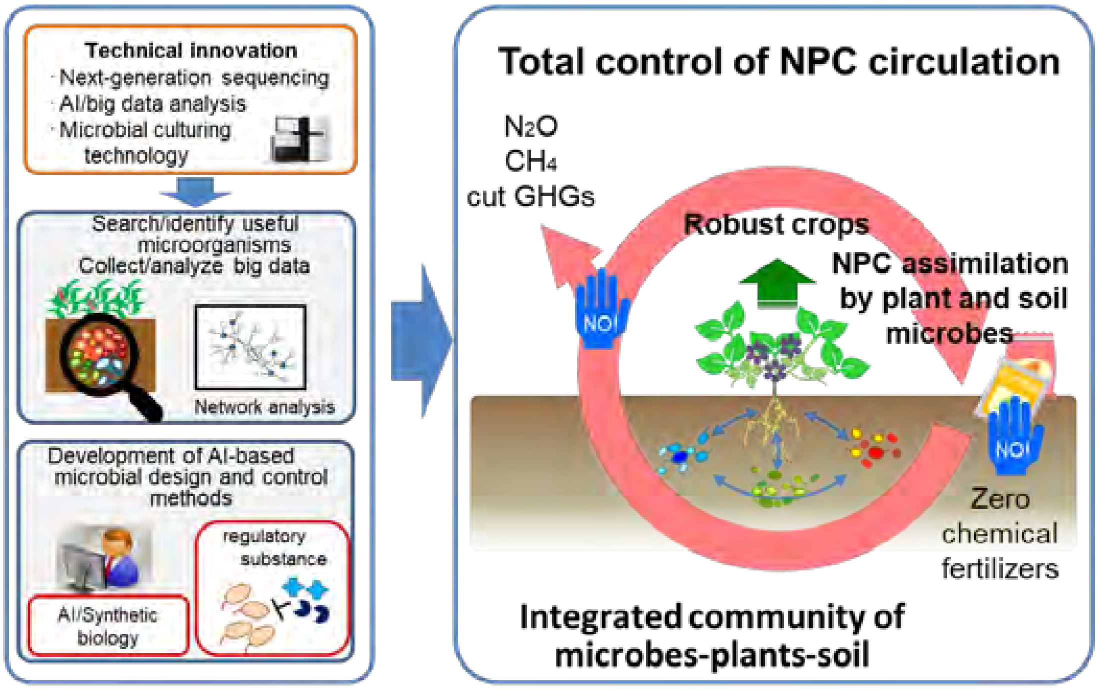

Figure 13 Conceptual diagram of technology development for the complete control of the soil microbial environment

(3) Aiming for minimum chemical pesticides through complete pest control

The aim is to establish a new pest control technology that makes full use of AI, robotics, and biotechnology, reduces dependence on chemical pesticides, and strives for a shift to agriculture that considers the conservation of the biodiversity. This will address current social problems such as maintaining and increasing biodiversity, ultimately reducing the environmental burden, and maintaining sustainable agricultural production. Pest control that fully utilizes physical and engineering methods and biological functions is indispensable to enable the stable production of food with minimum burden on the environment. Therefore, the following R&D examples are envisioned.

a) Development of new control technologies using physical and engineering techniques

The aim is to develop new technologies that may be applied to a wide range of pest species and will be based in a combination of physical control methods and engineering technologies such as AI and robotics to control only pest species who no inducing pesticide resistance (Figure 14).

Possible examples include the development of small robots to patrol a field and able to identify and count pests and other organisms, while removing only the target pests. It is conceivable to develop methods for the accurate identification of pest species using AI and new physical pest control technologies able to repel and/or kill pests using physical stimuli as elemental technologies installed in robots.

These developed technical elements will first be used on a stand-alone basis. Based on the development of the technology to date, some results are expected in the next five to ten years. The devices resulting from these technologies will be made smaller lighter to be installed in small robots or micro robots through national and international joint research collaboration with the private sector and overseas parties. The practical application of pest control robots able to integrate functions from predicting pest occurrence through to pest eradication is expected to be available approximately in 2050.

b) Development of new control technologies that fully utilizes biological functions

The aim is to develop novel technologies that are able to suppress the propagation of pests, or eradicate pests by biological strategies based on the elucidation of biological functions of insects such as inhibition of pest-reproduction (Figure 14).

Examples include technologies such as eradication of pests by hereditary manipulation of pests using symbiotic microorganisms (e.g.; producing only males or producing no offspring), or through modification of the gene function using genome editing methods that have developed rapidly in recent years. It may be possible to create super-efficient natural enemies of pests that can be active for a prolonged period even in harsh environments, such as an ambient temperature much higher than the optimum. Applying biological functions such as symbiotic organisms for pest control, the development of innovative pest control technologies is expected.

These technological developments are expected to produce pioneering cases first targeting specific agricultural pests in the next five to ten years. In the next phase, up to year 2050, it will be necessary to gradually expand the application to pests that are difficult to control with ordinary control measures.

This kind of research and development will make it possible to overcome problems such as resistance by year 2050 and achieve complete control of pests, which will ultimately reduce environmental burden, thereby achieving agricultural production and maintaining and increasing biodiversity.

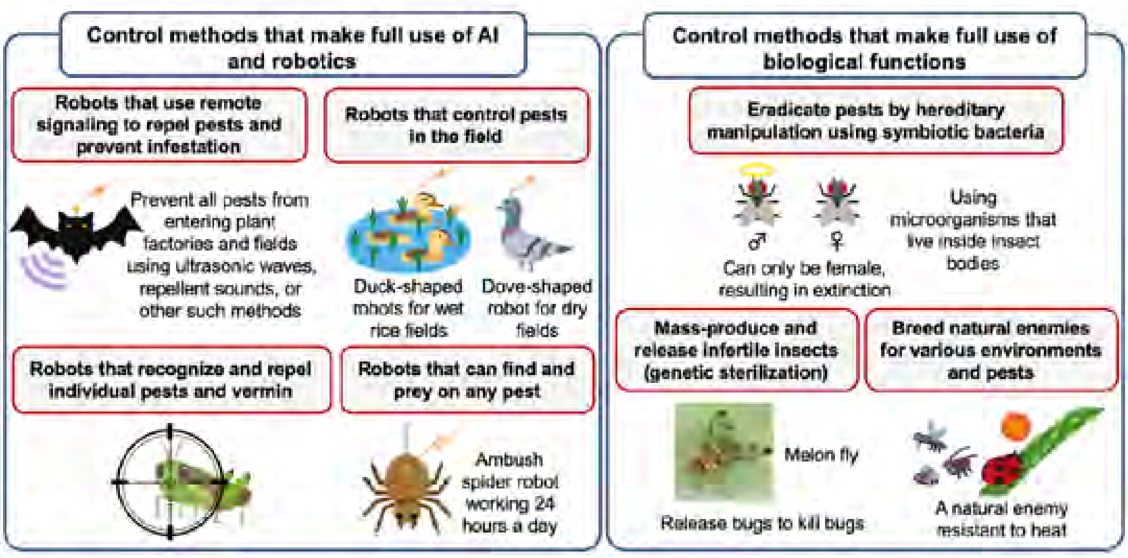

Figure 14 Conceptual diagram of new pest control technology making full use of robotics and biotechnology

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

<MS Goal candidate 2>

Developing solutions to eliminate food loss and waste and promote rational, health-, and environment-conscious food consumption by 2050

II. STATISTICAL ANALYSIS

Demand for food is expected to continue to rise. Two important approaches to meet the growing demand are to increase productivity further and to reduce food loss and waste.

In the agriculture, forestry, and fishery industries that comprise the supplier side, major causes of food losses and waste in Japan may include imbalances between supply and demand, in addition to annual fluctuations in productivity influenced by the seasonal and regional nature of produce, poor storability, and weather conditions.

Among the food industry and consumers that comprise the demand side, meanwhile, the causes may include problems with overstocking, overproduction, disposal of food before its expiration date, food leftovers, and so on. Therefore, in short, it is urgently necessary to 1) resolve the supply-demand imbalance on the supplier side, and 2) reduce food losses and waste and enable reuse of surplus food on the demand side.

Globally, reports suggest that over one-third of food goes to waste, primarily in the developed countries (FAO, 2011). In order to ensure that food is secured for the future in a sustainable manner and that mankind shares its limited supplies of food equally, it is essential to establish solutions to reduce food losses and waste with the leadership of, and cooperation between, the developed countries.

Japan has low food self-sufficiency and currently relies on overseas farmland equivalent to 2.4 times the area of its domestic farmland to produce its food. It is abundantly clear that pressing demand for food as a result of population growth worldwide, as well as poor harvests due to extreme weather, may have repercussions on our eating habits here in Japan. Despite this, Japan's food losses and waste are as great as 6.43 million metric tons a year (as of 2016), about half of which is accounted for by households (Figure 15). Action is needed to promote smart use of agricultural surpluses and reduce food losses and waste over entire food supply chains, from production to consumption.

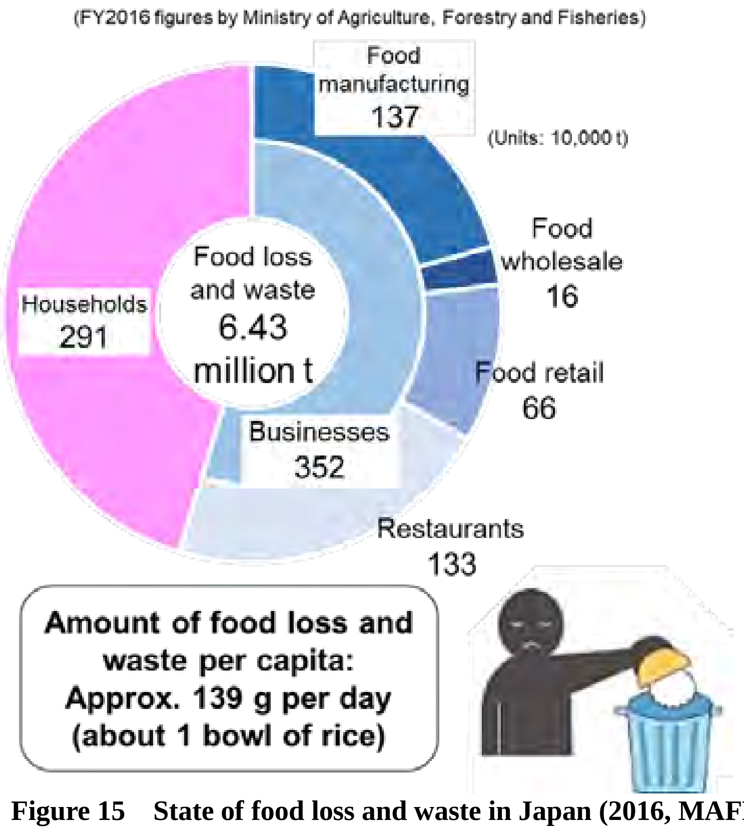

Figure 15 State of food loss and waste in Japan (2016, MAFF)

1. Structuring of MS Goal

(1) Current food losses and waste at the production and distribution stages, and related issues

Food production is predisposed to instability due to a number of factors, including the seasonal and regional nature of produce, and weather conditions, etc. Fresh produce and products have limited storability, and their quality deteriorates during the course of distribution, often resulting in disposal before they can be consumed. Today, 280–300 kg of food is lost per capita per year in developed countries, and 120–170 kg in developing countries. Food losses and waste occur primarily at the retailing and consumption stages in developed countries, and at the harvesting and processing stages in developing countries (Figure 16, (FAO, 2011)).

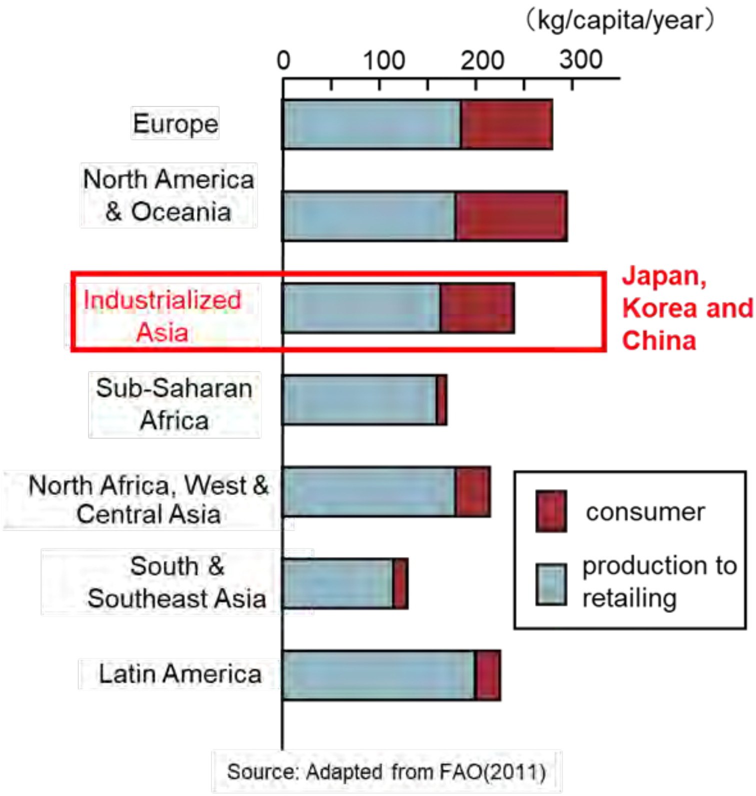

Figure 16 Per capita food loss and waste at the different regions

In developing countries, infrastructural issues are largely responsible for food loss and waste. Distribution networks (e.g., public transport, traffic and cold supply chains, etc.) are often underdeveloped, while producers and distributors may not be able to use appropriate modes of packaging or storage. These often prevent produced food from being delivered to where it is needed and when it is needed. Developed countries, on the other hand, not the small part of food to be disposed of at the consumption stage which includes households, restaurants and home meal replacements, due to excessively early expiration dates and overstocking (FAO, 2019).

One promising initiative to reduce food loss and waste worldwide is to make the established food distribution infrastructures in the developed country accessible to developing country, which should raise world's overall food supply capacity. At the same time, as aforementioned, over one-third of food goes to waste mainly in developed countries. This fact urges us to curb the “food wastage at the consumption stage”, which accounts for a large part of food loss and waste in developed countries at present, in order to ensure sustainable food supply in the future. For this purpose, it is desirable to “reduce” surplus as much as possible upstream in the supply chains. To this end, using of the burgeoning AI-based big data analysis will promote supply chain research with a focus on “reduce”, and may hold promise for drastic improvement in this issue.

Therefore, in research projects such as the second phase of Strategic Innovation Comprehensive Planning (SIP) issued by the Japan Cabinet Office, studies are underway to address such topics as non-destructive technologies for measuring the quality and freshness of products, storing and transport technologies for sensing quality and freshness data, development of cooperative distribution technologies and systems, and smart food supply chain technologies that utilize information during the production and distribution stages. In addition, obesity and lifestyle-related diseases are becoming a problem in developed countries, and it is also important to reduce surplus food generated at home by distributing food that contributes to personal health in a timely and optimal manner. For example, if we can efficiently match all supply and demand needs among stakeholders while improving personal quality of life, and can provide logistics solutions that utilize all types of transportation, we can expect food losses and waste in the supply chain to be dramatically reduced.

(2) Current food losses and waste at the consumption stage, and related issues

Japan reportedly wastes as much as 6.43 million tons of edible food a year, about half of which is accounted for by households.

A majority of food surplus at the consumption stage, including in households, goes to disposal. In Japan, food waste disposal costs local governments approximately 2 trillion yen annually, and domestic (household) waste accounts for about 70% of the expenses, while industrial waste accounts for about 30% (source: FY2016 Survey on Disposal of General Waste, Ministry of the Environment).

To address this, the Food Recycling Act was enacted in 2000, and while this led to reduction in food losses and waste generated by food-related businesses (manufacturers, distributors, restaurants, etc.), household food losses and waste did not reduce sizably. Subsequently, the Food Loss Reduction Promotion Act was legislated in 2019 in a strengthened effort to reduce waste at the consumption stage.

In 2015, France introduced a food waste prevention law to ban food-related business operators from intentionally making edible unsold food inedible, and to oblige them to find recipients for donations to enforce this law. The reduction of household food losses is not covered by this French law, however.

Food losses and waste always occur to a certain extent in households, and consequently do not decrease. Food is abandoned because it cannot be cooked, is left over due to an individual’s physical condition or preferences on the day, is purchased in unnecessary quantities, or deteriorates in quality due to decaying of fresh food, etc.

The current local government sorting and collection system is not suited to the reuse or recycling of household loss and waste. The first reason for this is that, unlike business-related loss and waste, the types and quality of household loss and waste vary greatly depending on the mode of consumption and the season, etc. Secondly, the garbage disposal units that are becoming popular for household use, with the support of local governments, are limited in terms of enabling production of fertilizer, etc. For this reason, reuse and recycling are not progressing in the current recovery system. Furthermore, the results of LCA (Life Cycle Assessment) evaluation of household food losses and waste for resource recycling differ depending on the residents’ degree of cooperation and effort, and on housing circumstances (Liu and Kondo, 2008). Therefore, it is necessary to consider the residents’ circumstances in terms of their living environment and locality when developing and evaluating efficient resource recycling systems suited to each community.

Furthermore, it is necessary to construct an innovative reuse and recycling solution that makes full use of surplus foods and food residues generated in households and communities. One possible solution may be a supply chain for surplus foods and residues using IoT and AI. This system would make identification of new demand and matching of supply and demand more efficient, and effective use of surpluses and residues in the region would be likely to expand. Another possible solution for homes is the likelihood that making cooking appliances multi-functional, etc., and their linkage with IoT and AI, will dramatically improve reuse and recycling at the site of food consumption. For example, IoT and AI technology will enable food quality to be “visualized”, allowing alerts to be issued ahead of expiration dates. In addition, any white cooked rice left over at dinner is currently frozen, thawed, then reused as white rice again; however, if multi-functional cooking appliances that can dry, crush, and ferment, could be developed, the leftover rice could be converted into sweets, sugar, etc., and rice disposal would be drastically reduced.

Converted food surpluses could help provide food suited to the health and preferences of the individual, and that in turn could help individuals to become healthier by preventing obesity and lifestyle-related diseases, and also to enjoy food more (in terms of taste, etc.). In that case, individuals would be more motivated to pursue these ends, which could promote continued and sustained effort. In short, promoting research focused on reclamation of food surpluses contributing to personal quality of life may lead to the development of innovative technologies, which could enable substantial reductions in food losses and waste from households.

In Europe, efforts are progressing to increase protein supply due to concerns about a shortage of protein sources in the future (“Protein challenge 2040” https://www.forumforthefuture.org/protein-challenge), including production of “imitation meat” from plant-derived proteins (Schreuders et al., 2019; van der Weele et al., 2019) and of “cultured meat” from bovine skeletal muscle stem cells (Post, 2014). Similarly, there is increasing research into utilizing insects as food by exploiting their high protein conversion efficiency (Huis, 2013). In Europe and elsewhere outside Japan, moreover, attempts have been made to grow insects using food loss and wastes (Varelas, 2019) and to utilize insects as feed for aquaculture (Henry et al., 2015). In Japan, one example of food recycling is the establishment of an “eco-feed” system that collects and processes food losses and waste generated during food production and manufacturing, feeding them to livestock (Sasaki et al., 2011). Another unique example is a practical technology that eliminates the smell of fish meat by feeding cultured yellowtail snapper fish with the mixed peels of citrus fruits (yuzu and iyo) that are discarded in large quantities in the areas where the fruit are grown (Fukada et al., 2014; Mizuno, 2018). As mentioned above, there are examples of efforts to recycle food loss and waste both in Japan and overseas; however, the amount of waste at the consumption stage in developed countries is still high, and further reduction measures are required. In particular, it is necessary to strengthen research into mechanisms for thoroughly recycling food loss and waste generated at the household and regional levels, taking individual circumstances into consideration. In addition, there are vast untapped resources in areas used for agriculture, forestry, and fisheries in Japan. If these unused resources could be incorporated into the food cycle through biological agents such as insects in the future, they would contribute greatly to solving global food problems.

2. Science and Technology Map

Research into food losses and waste has been on the increase (Figure 17), particularly in the last five years. While much of the literature from around 2000 is in the fields of zoology, sociology, nutritional science, and oceanography (data not shown), research in the fields of transportation science technology, transportation, and telecommunications has seen growth in recent years.

This indicates growing momentum toward actively managing supply-demand mismatches in food from the stages of production through consumption (i.e., in food supply chains), which are largely responsible for food losses and waste. To reduce food losses and waste, it may be useful to link food supply chains to AI-based information networks, particularly IoT and ICT, which have progressed rapidly in recent years. However, research in this field has still received little attention, with only three studies in 2014 and eleven in 2018. The key characteristic of fresh foods is the fact that they deteriorate in quality or decay during the course of the distribution process after harvest, and eventually become worthless. Therefore, future application of IoT to food distribution should take into consideration not only information about the quantity of food, but also about its quality (such as quality changes over time).

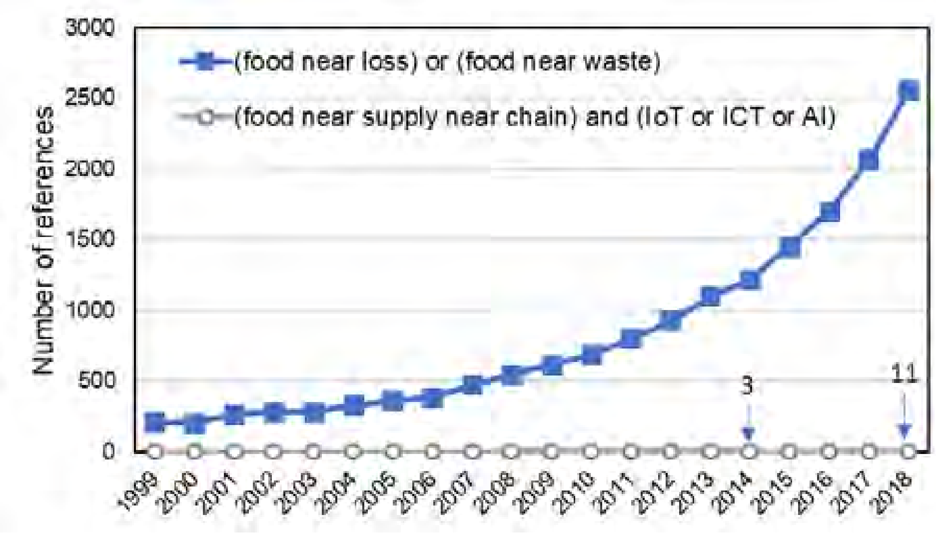

Figure 17 Research trends in food losses and waste, and food supply chains (Clarivate Analytics, Web of Science)

When considering the active use of food losses and waste, one solution is to convert them into energy or materials. Among the existing research projects on food losses and waste, studies addressing these topics account for approximately 24% and 14%, respectively, suggesting a relatively large interest (Figure 18). Methods of converting food to energy or materials include smart use of biofunctions, in addition to chemical and physical methods. Although related research has been conducted to date, however, it accounts for only about one-seventh of the research into energy and materials conversion overall. Meanwhile, recycling of food losses and waste has been the subject of highly successful projects such as one on fermented liquid feeding (Sasaki et al., 2011), but such studies represent as little as 5% of all research projects on food losses and waste. This area of research is far from being advanced due to issues of social acceptance and technical difficulties. Another potential approach to recycling would be to take advantage of Japan’s ocean resources to explore the possibility of aquaculture applications for food losses and waste; however, little attention has been paid to this area so far.

One means of reducing food loss, waste, or disposal is the method of “reprocessing” into foods with excellent nutritional benefits and taste by using edible resources such as surplus agricultural products, non-standard products, and by-products as food materials. In recent years, the development of 3D printing technology has been remarkable (Figure 19). Such 3D printing technology can produce small quantities as well as a large number of individual items and is thus considered a promising means of enabling individuals to select various foods in the food field. However, there are actually few studies on the use of 3D printers in the food field (Figure 19 orange) as opposed to the industrial field. In addition, the materials used in the food field are limited to ingredients that are easy to put into the printer.

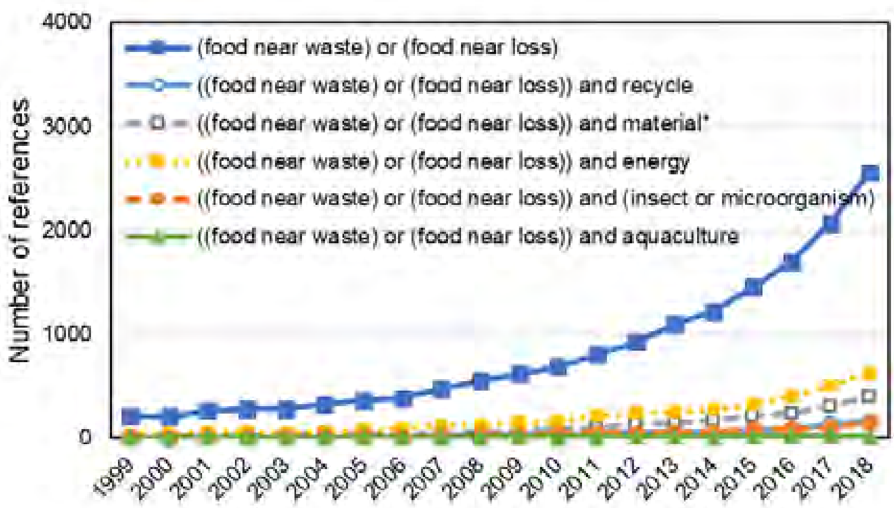

Figure 18 Research trends in food losses and waste focusing on recycling, materials/energy conversion, insects/microorganisms, and aquafarming (Clarivate Analytics, Web of Science)

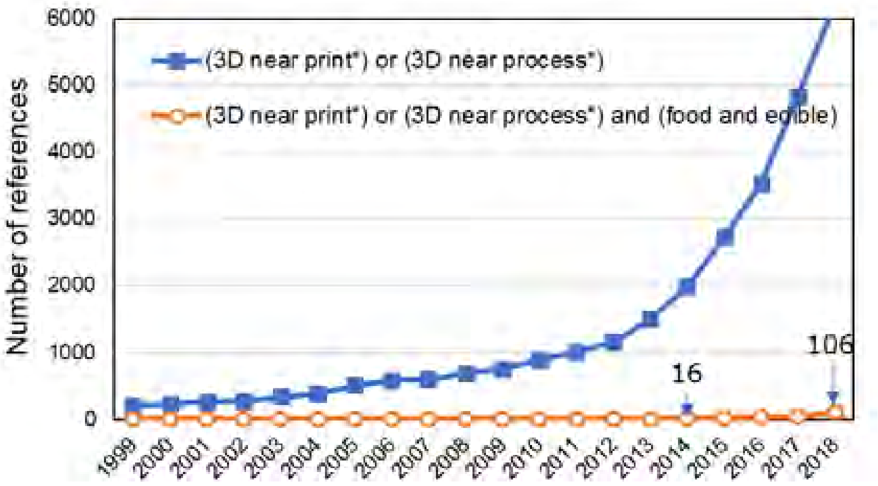

Figure 19 Research trends in 3D printing and their use in food field (Clarivate Analytics, Web of Science)

III. SCENARIO FOR REALIZATION

1. Realization of Goals

In order to support the ever-growing world population, it is critical to create disruptive innovations capable of drastic reduction of food losses and waste, not only in Japan but also worldwide.

Therefore, to eliminate food losses and waste and promote rational, health- and environment-conscious food consumption by 2050:

First, it is necessary to accelerate the practical use and implementation of AI in every stage of food supply chains to eliminate mismatches between supply and demand. Based on this requirement, by integrating information at every stage of the food supply chain and converting it into big data, the aim is to create a system that can match all the needs of supply and demand in cyberspace and to deliver food according to the health requirements and tastes of individuals without loss and waste. This system will help to largely reduce food loss and waste in the supply chain.

Second, we should aim for a system at home that reuses the food that cannot be handled by the above supply chain system. If in the case that food loss and waste still occur, another system that reuses and circulates the loss and waste within the local region will be necessary (circular economy).

Specific examples of research and development projects required to realize these solutions are as follows:

(1) Establishing "Zero-food-loss and waste" / AI-based supply chains driven by quality and personal information

We will focus on the development of a data-driven supply chain that can match and deliver all supply and demand needs in real-time in cyberspace among stakeholders, such as food producers, food consumers, and other consumers. To do this, a wide range of technologies should be introduced and integrated throughout entire food supply chains. Such technologies include dynamic pricing (systems that adjust demand by changing prices according to current supply and demand conditions) and the sharing economy (a mechanism to widely share and exchange personal goods, technologies, services, and other items), etc.

Foods in particular differ from other industrial products in that production and shipment volumes vary significantly depending on the season, weather, and region, while their quality changes over time (i.e., they deteriorate and age) during transport. Therefore, building suitable supply chains for food is very important and is expected to be very challenging. (Figure 20).

In particular, the following research topics are envisaged:

- Collecting big data on the manufacturing, distribution, and consumption stages both in cyberspace and in physical space
- Establishing data-driven AI-based supply chains that cover the production, distribution, and consumption stages

By developing these technologies, by 2030 information in the food supply chain will be matched in real-time, then a prototype of a "data-driven, AI-based supply chain system" will become available for the public. This system for the public will shift logistics, making it interactive and circular, and will be able to deliver the necessary products to the people who need them. These technologies will dramatically reduce loss and waste generated from the food supply chain. Furthermore, by 2050, information on food quality and personal health and preferences will be integrated into the abovementioned cyber-logistics information, operating on a single platform. Then, all supply and demand needs will be matched in real-time, reducing food loss even more substantially.

(2) Solutions to reduce food loss, waste and residues in households and communities

a) Reuse solutions at household

For households, we will investigate a new food supply system that minimizes food residue and simultaneously improves personal quality of life (QOL). For example, the storability of perishable fresh products and other surplus foodstuffs at room temperature will be improved by drying and powdering. However, in turn, their freshness, shape, and texture, etc. will be lost. Therefore, if an AI-based 3D processing and cooking system (AI chef machine) is developed that can automatically and faithfully reproduce 3D food, such as raw cut apples from dried or powdered food materials, it will reproduce and process foods matched to individual health requirements and preferences, further reducing food loss and waste at home. To realize an "AI chef machine" for the first time in the world, the following research will need to be accelerated: techniques for cell culturing; thin films and laminations; 3D reconstructions that have been progressing remarkably, though not in the food industry; and the development of AI to determine suitable processing methods that take into account personal preferences and health conditions. Combinations of these technologies will also be required.

Additionally, food and menus that meet individuals' health requirements and preferences will need (1) to clarify the function of food for human health, (2) to establish objective/scientific indicators to evaluate food quality (taste, aroma, texture, etc.), and (3) to clarify the mechanism of human taste/palatability scientifically as well as create a system that integrates this information comprehensively so that it can be assessed. These systems required a “brain science” approach to find out how people perceive taste and palatability. By promoting these types of interdisciplinary research, solutions will be created that will promote rational, healthy, and environment-conscious consumer behaviors (Figure 21).

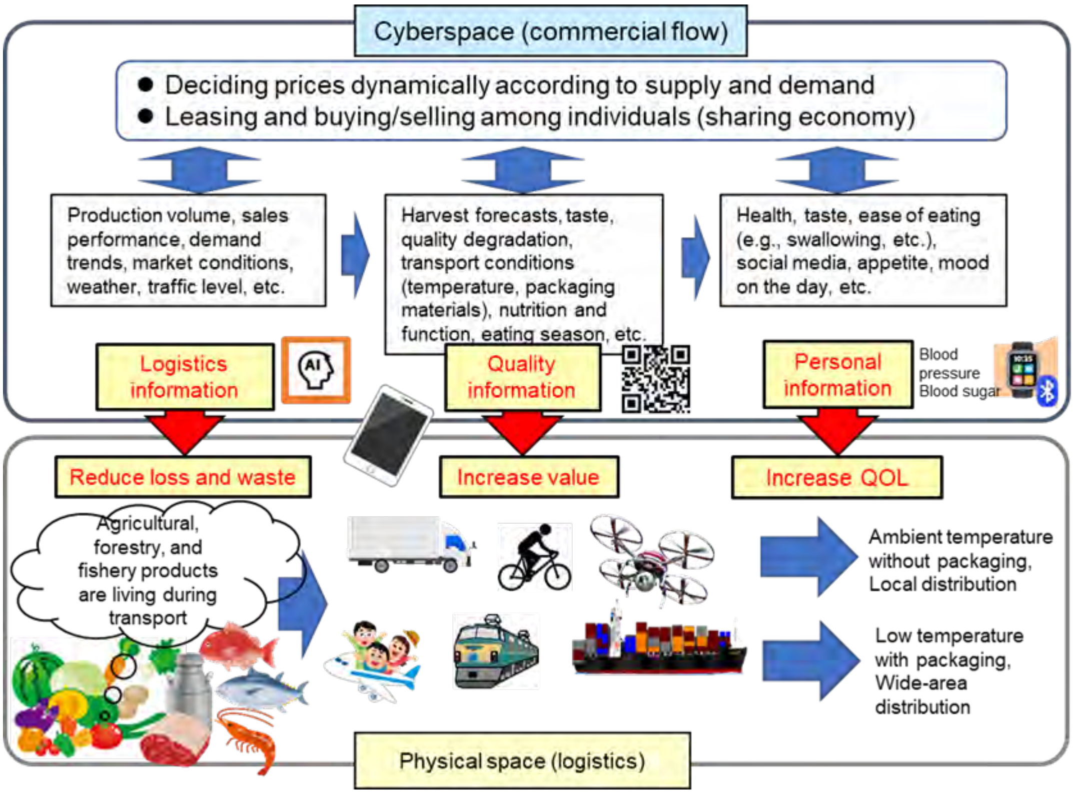

Figure 20 Establishing AI-based supply chains through information-driven control of distribution / quality / personal information

In particular, the following research topics are assumed:

- Development of foodstuffs suited to a 3D food printing and cooking system (an “AI chef” machine)
- Development of AI-based food plan recommendation systems that are driven by data on nutrition, exercise, health functions, and personal preferences
- Clarification of the mechanism for palatability and sensing taste (“brain science” research)

Researching these technologies will enable prototypes of the following systems and technologies to be developed and become available for public use by 2030: an AI-based printing and cooking system that enables 3D food reproduction, technologies to standardize foodstuffs suitable for the device/system and meal delivery systems based on the tastes of a specific age group, etc. Furthermore, by 2050 variations in available food materials and processing methods will increase by using the AI supply chain described above in (1), and then a supply of personalized foods coming from big data visualizing individual’s health requirements and preferences will become possible. This supply chain is expected to grow globally and to contribute to a substantial reduction in food loss at the consumption stage.

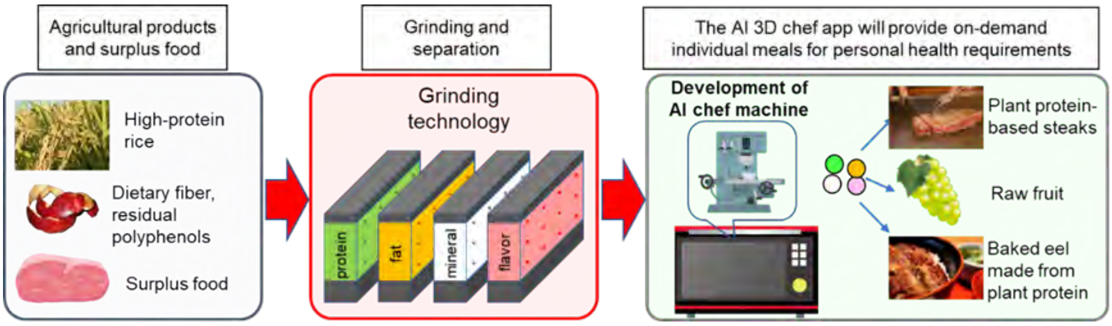

Figure 21 Personalized food provision system tailored to individual users' health and preferences

b) Recycling solutions for communities

Not only for reducing food loss and waste, adopting this new approach will free up abundant organic resources that have not been fully used in agricultural, forestry, and fisheries in Japan. Resource recycling systems will be necessary that do not place a burden on the environment when these unused resources are efficiently converted into food, feed, and energy.

Currently, in Europe, protein production methods that have little impact on the environment are attracting attention, such as the production of cultured meat, etc.

For example, if all the unused organic resources, such as food loss, waste, surplus, and agricultural products that are not up to standard, livestock excreta, vegetation, land residues, etc. can be converted into materials like protein, fuel oil, and feed, among other items, and then incorporated into the food supply cycle by using the high protein synthesis capacity of insects, it may potentially contribute not only to reducing food loss and waste but also contribute significantly to a stable food supply (Figure 22). If the abundant unused resources in rural area can be converted into protein materials and feed for aquaculture by using insects, an aquaculture industry that more effectively uses the vast ocean area could be promoted. For these ideas, for instance, the following research topics are assumed:

- Establishment of technologies to efficiently produce protein from food and land residues by using the outstanding functions of insects and microorganisms.
- Cascading use of surplus agricultural products transformed into food ingredients by the biofunctions of microorganisms and/or physics
- Evaluation of CO_2 absorption capacities of marine algae and creation of an offshore environment optimized for aquaculture

As these technologies are developed, basic technologies will be completed for more efficiently recycling unutilized organic resources, including food loss, waste and residue, through biofunctions such by insects, etc. These technologies will be customized for every variety of fish for farming, and they will be implemented in model local region(s) by 2030. By using the above mentioned AI-based supply chain system, the logistics of food residue and unused resources will be optimized. As well unutilized resources from local regions will be converted into various and high-added-value materials, and then the local production–local consumption and semi-self-sufficient society will be brought about. It is expected that these recycling technologies, when they are developed, will be used both in Japan and globally, leading to a worldwide zero-emission society.

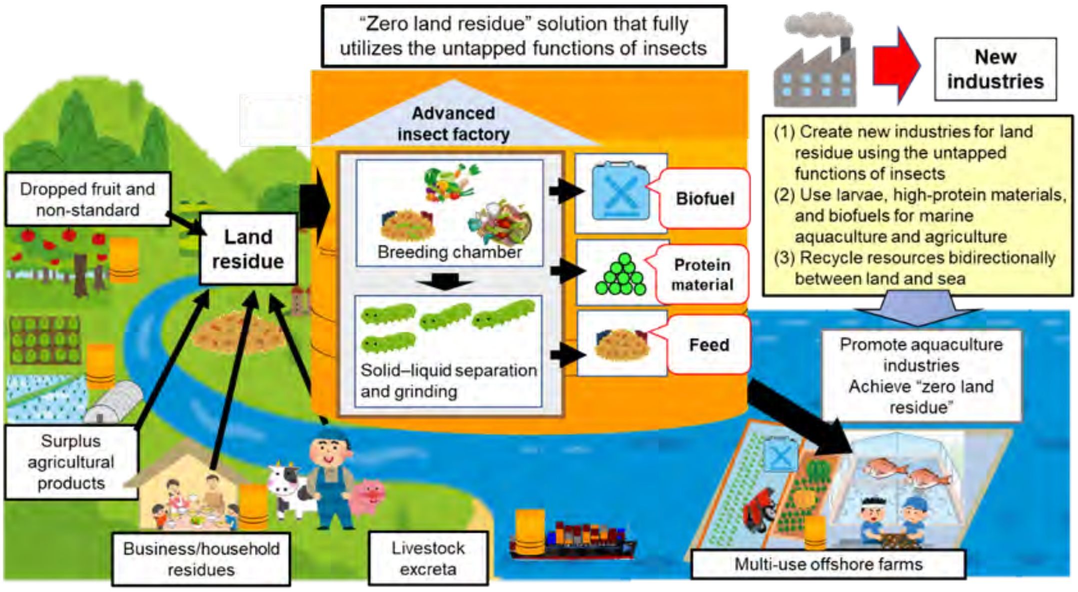

Figure 22 A new solution for zero food waste and other food residue

<MS Goal candidate 3>

Establishing a Robust Agricultural, Forestry and Fisheries System Which Can Adapt to Sudden Weather Changes by 2040

II. STATISTICAL ANALYSIS

1. Structuring of MS Goal

With the intensification of global warming, the future climate change will be more intense, meteorological anomalies may occur frequently (IPCC, 2014). If this trend continues, for example, we can imagine that due to the continuous intensifying of intense heat in summer and the unusual warmness in winter, the planting and harvesting time of rice and wheat are disordered, thus it will be difficult for farmers to rely on their accumulated agricultural experience and intuition for stable production. In addition, the intense heat in the summer makes it difficult for people to work outdoors, and typhoons and heavy rains are frequent. So, in order to flexibly operate without missing the optimal harvest time of crops, it is necessary to consider a 24-hour operation system, including night.

Therefore, in order to ensure the stability of food and increase production,1) It is necessary to be able to previously detect troubles of crops, plant diseases and insect pests that cannot be found by human eyes. 2) Quickly find the best responding based on various information.3) Take flexible countermeasures regardless of day and night.

(1) Growth information technology for crops, etc.

In the crop growth information analysis in Japan, it is collected agricultural environment information and cultivation information. As for the measurement of agricultural environmental conditions, in addition to field servers and other technologies for environmental measurement in farmland, meteorological data provided by the meteorological agency can also be used. The technology of meteorological information that can respond to analysis by 1km mesh or 50m mesh smaller geographical division has been developed and put into practice (Fukatsu and Hirafuji, 2004; Ohno et al., 2016).

To respond quickly to rapid sudden weather changes, regarding the growth and cultivation information of crops, the growth situation was confirmed by the contact SPAD chlorophyll instrument and now is replaced to non-contact type such as the near-infrared digital camera, which has improved the efficiency. Moreover, the harvest and taste sensors are installed on the harvester, and the yield and taste maps are made from satellite positioning information. Measurement ICT has been steadily progressing over the past 15 years (u-Japan concept; Ministry of Internal Affairs and Communications, 2004), however, it is still not enough to use sensors as IoT.

In the future, it will be necessary to promote the use of IoT to change the mechanism of the agriculture, forestry and fisheries production system. Obtaining high-resolution bioimaging information outdoors is key to solving the problem with sensing technology.

a) Predictive detection by approaching sensing

In the cultivation process, it is necessary to understand information such as the biological information of plants that humans cannot recognize, sensitive changes and crop quality. At present, sensing of fluorescence characteristics of agricultural products is in a practical use. Although it is effective for indoor fruit selection and food inspection, it has not yet been used outdoors. The odor sensor can accurately detect the odor of the target. However, the use of IoT related to the determination and detection of various components is still in the fundamental technology research stage.

In the future, in order to sense the growth of crops and changes in freshness after harvesting at a predictive level, it will be necessary to accumulate sensing information worldwide, standardize judgment information, and implement technology as IoT.

b) Advancement of wide area sensing

With the continuous development of UAV technology, it is feasible to collect comprehensive information about each field, crops planted in the field and soil information through UAV sensing. Moreover, a wide range of satellite images are used for growth information mapping in Hokkaido, Japan (Otsuka et al., 2001).

By continuously applying these technologies and using supercomputers, we can issue more accurate weather forecasts. It will be required to get early detection of diseases and pest damage by enabling observation of a wider range of fields in a short time and with high frequency under sudden weather changes. Particularly, satellite image observation through optical sensors that cannot be measured in time when there is a lot of cloud, and UAV observation that cannot be used in stormy weather are insufficient, more accurate high-performance small radar (SAR) satellites are required to be effectively used.

(2) AI analysis technology to judge work execution

In recent years, with the development of computer science, the availability of AI related technologies such as multivariate analysis technology, deterministic reasoning technology, and image recognition (individuals, shapes, and behaviors) technology has rapidly increased, and it has been possible to perform automatically. On the other hand, it is necessary to consider how to properly manage big data including weather data from supercomputers (CRDS, 2017).

a) Maximize the results of advances in computer science

In 2021,"Fugaku", which is 100 times faster than the currently Japanese supercomputer "Kei", will begin operation at RIKEN. "Fugaku" captures big data observed by meteorological satellites and radar. And it will be improved by the prediction accuracy while assimilating it with analysis data during the calculation in Japan. Maximum utilization of the advances in supercomputers will become more sophisticated, for example, it is a possibility to highly advanced cooperation with applications such as map information other than weather information.

Research on the use of AI-related technologies is continuing worldwide, such as the application of deep learning based on environmental data, growth data, pest and disease data, and operation management data (Shinjo et al., 2015). However, no analysis has yet been made to clarify the basis for AI judgment.

Moreover, for future AI analysis, full use of the supercomputer, it is also necessary to effectively utilize “explainable AI” that can clarify not only the results but also the reasons and basis for judgment (Samek et al., 2017). Furthermore, it is necessary to develop technologies that quantify and accumulate formal knowledge, find new criteria, and dramatically increase the accuracy and speed of judgment.

b) Advancement of big data utilization

Big data that are expected to be applied in the agricultural field include meteorological data, specific soil moisture and fertility, leaf surface wetness and other environmental information, crop physiological information, damages from disease and insects, production management information and agricultural work management information etc. The competitive advantage through advanced sensing technology and metadata management can increase the value of big data.

So far, the development of useful agricultural applications based on AI analysis has been facilitated, but AI analysis using big data has not always been efficient due to poor management of metadata. In the future, in order for AI to make appropriate business judgment or technology choices based on in comprehensive knowledge, it is necessary to accumulate high quality data on a global level.

(3) Agricultural machinery and robotic system replacing specific operations with engineering

In the Agricultural Forestry and Aquaculture Innovation Technology (2014-2018) in the New Era of the first phase of Strategic Innovation Comprehensive Planning (SIP) issued by the Japan Cabinet Office, the automatic driving technology for agricultural machinery targeting paddy field operations and land-use agriculture is developed (Cabinet Office, Government of Japan, 2018). In the second phase of SIP, the movement between fields of automated agricultural machinery is under development, and the automatic driving technology is beginning to adapt to vegetables farm work, etc.

a) Advanced robot hand manipulator-related technologies

Regarding the research and development of robot hand and manipulator-related technologies are progressing globally. For example, in Japan grafting robots, which can perform grafting automatically after providing spike and rootstock manually, have been used in seedling centers and other places since about 2000. Also related to facility horticulture, strawberry picking and boxing robots have been commercialized by 2015 (Hayashi et al., 2010).

However, since it is a high-cost robot limited to a specific crop, it has not become popular. Self-propelled small harvesting robots that can respond to multiple crops by replacing the end-effect or has begun to be introduced to agricultural work sites, are expected to be applied to other crops. There are still many issues to deal with before reaching the practical use. In order to greatly reduce the use of pesticides and fertilizers to achieve a high productivity, development of high-precision control end-effectors will be required.

b) Continuous work by small distributed cooperative robots

In future, more advanced robot technology will adapt to agricultural machinery, vehicle-type agricultural machinery and operation machines are required to save energy by electrification for drive and control systems effectiveness. In order to reduce the harmful effects of the use of agricultural machinery on the environment, the use of fuel cells should also be considered.

In order to realize the automatic operation of long hours through day and night to adapt to sudden weather changes, it is required to specify the function of error recovery in emergency. However, technologies such as elevators capable of self-checking, diagnosing, and recovering after an earthquake have not yet been applied to agriculture, forestry, and fisheries. In addition to the development of the automatic power supply function, it is necessary to develop a highly difficult system that can automatically notify defects and perform regular maintenance.

On the other hand, "Swarm Intelligence", which is a kind of AI technology that enables sophisticated operations while exchanging between individuals for a specific purpose within the group, has attracted attention. This technology is expected to advance the development of underwater exploration robots (Quraishi et al., 2019). The robot tractor realizes the operation of multiple units in which four units work together (Noguchi, 2018), but the robot itself does not make AI judgment, and the connected work devices are not sufficient for IoT.

2. Science and Technology Map

There are many studies on climate-changes compared to machine-learning related to AI analysis. (Figure 23). AI related research is increasing along with research on crop productivity and sensing. In addition, accurate and detailed weather forecasts are very important to quickly find the best treatment method based on weather forecast. In 2019, the Meteorological Agency began to forecast heavy rain early through the Meso Ensemble forecast system, improving the prediction accuracy of typhoon course. In the future, AI technology is expected to dramatically improve the accuracy of linear precipitation zones and typhoons prediction.

Regarding AI, according to the R&D overview report by JST's Research and Development Center (CRDS), in the field of systems and information science, the percentages of AI patents by countries using the numerical data of the AI Index Report 2018 are as follows: The US accounts for about 30%, South Korea and Japan are about 16%, and China is about 13%, and since 2008, China's growth has been slowing down.

In recent years, the increase in the number of papers about automation / AI research is remarkable, but the agriculture field only accounts for about 5% of all research fields (Figure 24). In the future, it will be important to strengthen the competitiveness of AI research and development in Japan by increasing the intellectual property and papers of agricultural AI.

Based on the above, Figure 25 shows a technical map that aims to create a society that can ensure stable food supply and increase production even if sudden weather changes.

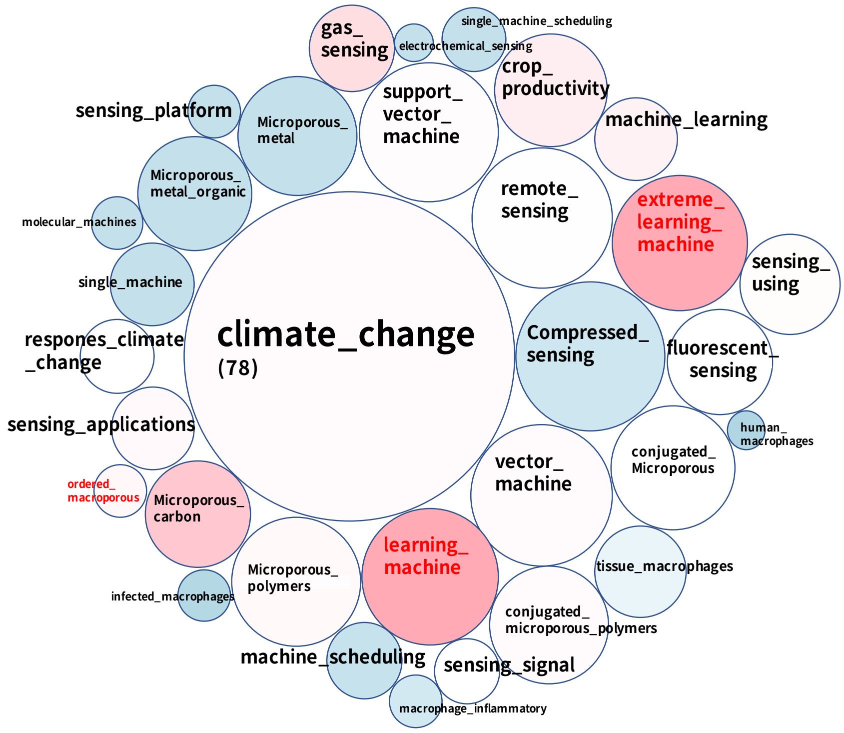

Figure 23 Research trends in recent years related to climate change, machinery, crops, and sensing

(Source) Ministry of Education, Culture, Sports, Science and Technology, Academic Policy Institute, Science map2016, NISTEP REPORT No.178, Processed in October 2018 (Search terms: machine, climate change, crop, sensing, partial matching search, visualization field is the all-field, changes from 2010 & 12 to 2014 & 2016)

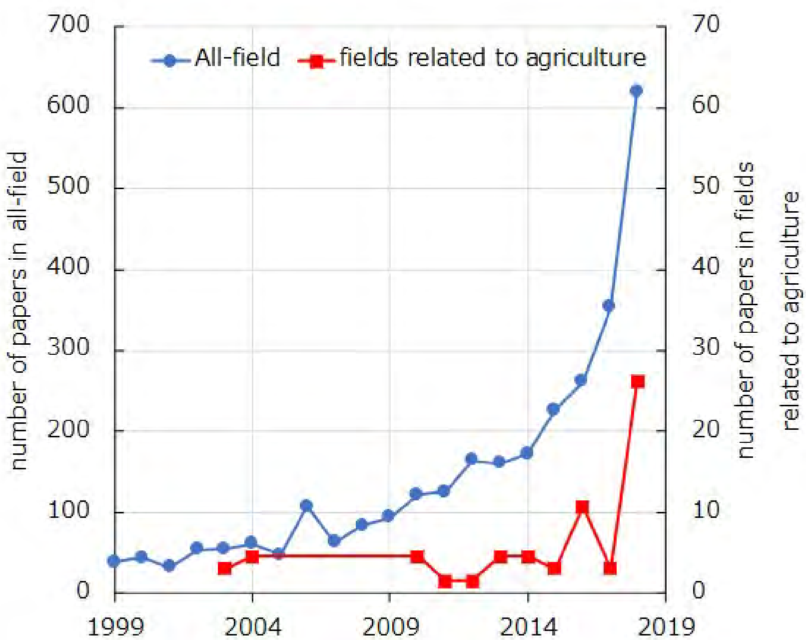

Figure 24 Research trends on machine, automation and artificial intelligence in Japan and overseas from 1999 to 2018 (Clarivate Analytics, Web of Science)

(Search terms: machine*, auto*, intelligen* and agriculture*)

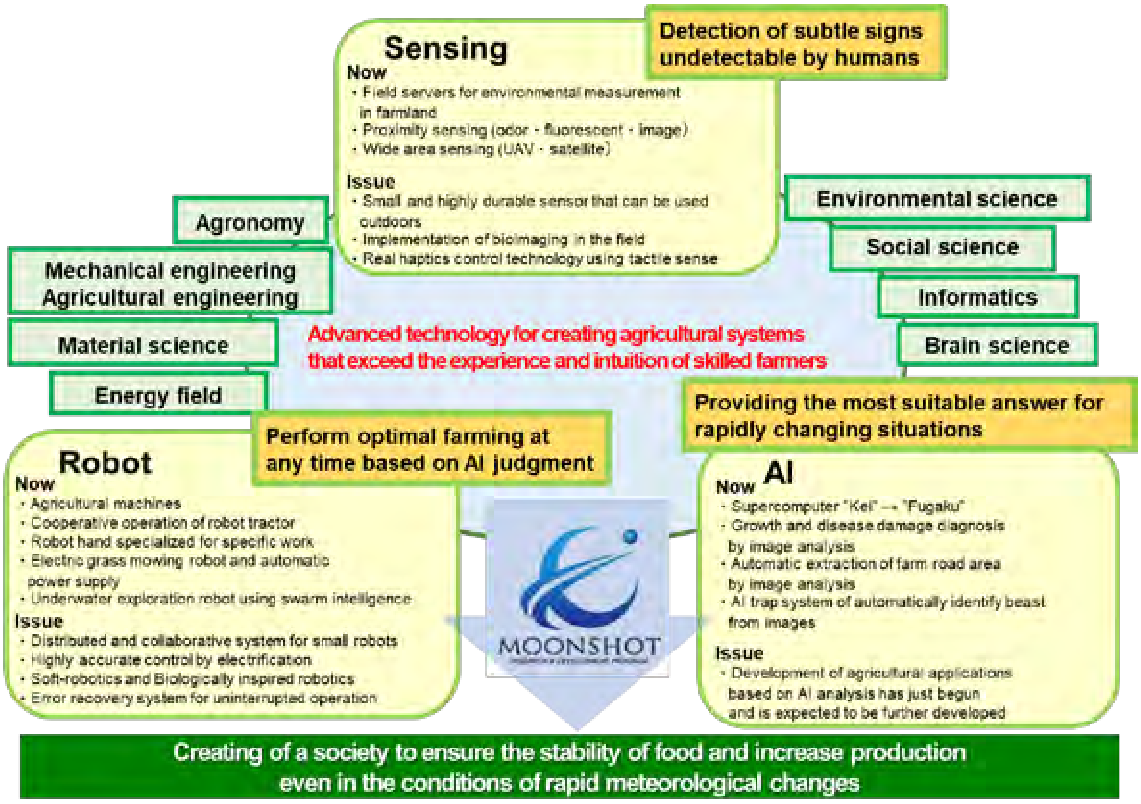

Figure 25　A technical map that aims to create a society that can ensure stable food supply and increase production even if sudden weather changes occur

III. SCENARIO FOR REALIZATION

1. Realization of Goals

In the future, it is anticipated that there will be further expansion of drastic fluctuation of weather, so stable production is impossible with long-term experience and intuition alone. In brief, it is necessary to build tough agricultural, forestry and fisheries systems based on global perspectives, which can respond to rapid weather changes. From those perspectives, the following examples of research and development are expected, using related research results by the other MS goals.

(1) Exceed the 5 senses of excellent laborers (Develop innovative sensing technology for super-precision farming)

High-resolution outdoor bioimaging information that makes full use of sensing technologies (smell, ultrasound, non-visible light, etc.) need to measure the crops' signs that cannot be found by the five sense organs of human.

Therefore, image data is used to quickly and automatically acquire and accumulate large-scale or scattered farmland information (growths, diseases and terrains, etc.). In addition to conventional near-infrared sensors, the development of sensing technology that can be used for advanced decision-making from the use of fluorescent image information and extremely weak sensing information such as quasi-electrostatic fields is also expected.

By developing these technologies, it will be able to understand the health status of individual crop and ensuring the maximum yield and quality, and minimize the losses caused by natural disasters even under weather changing conditions. Based on the above, anticipated sensing technology will be available in 2030, enabling accurate growth management of individual crops and real-time sensing of freshness after harvest. Thus, in 2040, a sensing system that exceeds the five senses of skilled laborers will be implemented worldwide.

(2) Expand the accurate assessments of skilled laborers (Development of an AI analysis system)

While collaborating with the other MS goals, in terms of artificial intelligence development, big data related to agriculture, forestry, and fisheries will be built using the environment-resistant and efficient sensing system developed in (1), and an AI analysis system that provides useful solutions.

For example, in addition to forecasting one week before the typhoon and half a day before the heavy rain, it will be possible to accurately predict the extent and duration of the heavy rain due to the linear precipitation zone by high resolution prediction of supercomputer "Fugaku". As a result, it is expected to build a system that provides forecasts of climate changes from a global perspective, perform crop damage and risk hedging of shipping plan, select new planting periods, and create production areas globally.

By developing these technologies, an artificial intelligence system that implements risk hedges from a global perspective will be able to greatly support farmers' judgment for management. In 2030, the AI analysis system can issue instructions for emergencies and formulate early harvests and delivery plans one week before the typhoon strikes. In 2040, farmers can use the system, to realize a society that can flexibly and practically respond to sudden weather changes.

(3) Exceed the skills of skilled laborers (Creation of intelligent farm with uninterrupted operation)

While collaborating with the other MS goals, according to the big data and instructions of cultivation and operation obtained in (1) and (2), autonomously develop the farm work. The intelligent farm will be used for adapts to sudden weather change and expected to operate 24 hours a day for 365 days.

At the intelligent farm, for example, it is expected to construct a system in which many small robots perform cooperative work in large-scale fields or perform shared work in many small-scale fields by utilizing "Swarm Intelligence (a dramatic technology development) ". A system in which companies can seamlessly construct production, harvest, preparation, and shipment by connecting urban and rural spaces is also conceivable.

It will be built a recovery-system that can continue working without human intervention, detect subtle changes of crops by edge computing that reduces communication delays, and work quickly based on this information. And it will be expected to develop small robots with strong environment-resistance in harsh weather, and soft-robotics will be adapted to end effectors for variable work.

Based on the above, aiming to the realization of stable food supply and increased production at the global level, even sudden weather changes occur, they will not cause a shortage of rice due to the chilling damage, like what happened in Japan in 1993. At first, the main R&D of crops production will be executed on grains such as rice and wheat, and vegetables such as tomatoes and cabbages, in 2030, prototype of robots that can implement the cultivation and operation plans suggested by the AI analysis system will come out. In 2040, the integration of innovative sensing technology and artificial intelligence will be realized, and the first model of agricultural, forestry and fisheries system will come out to improve global productivity.

IV. CONCLUSION

Based on the above, the following three MS goal candidates are determined.

MS Goal Candidate 1: Overcome constraints to water, fertilizers, and other resources by fully utilizing the biological functions of nature by 2050.

MS Goal Candidate 2: Developing solutions to eliminate food loss and waste and promote rational, health-, and environment-conscious food consumption by 2050.

MS Goal Candidate 3: Establishing a Robust Agricultural, Forestry and Fisheries System Which Can Adapt to Sudden Weather Changes by 2040.

When these MS goals are realized, all R&D shown in this IR will not be carried out using the MS research fund. Instead, MS R&D proposals will be collected widely from Japan and abroad including R&D that is not shown in this IR. MS projects will be focused on R&D suitable for the role of the seed money accomplished by the fund, and following concepts, 1) high risk, high return R&D that is not able to be addressed by private companies or other R&D programs, 2) fundamental R&D (such as DB construction) that induces voluntary R&D by private companies, etc.

In addition, collaboration with domestic and foreign R&D projects and voluntary R&D investment by private companies will be promoted under the Program Director (PD) by organizing a council that gathers relevant industry, academia and government officials. Finally, MS goals will be realized by integration/engineering with the above research results.

Furthermore, discussions about ELSI will continue in parallel, in order to take a strategic approach towards social implementation of the research results.

In addition, each candidate as the 25 Mission target examples (Figure 2, page 6) proposed in the Visionary conference, relating to the agriculture, forestry, aquaculture and food industries, is related to the following content.

Expands biodiversity in global agriculture by 2050

Eliminate food waste and provide everyone with the necessary food quickly by 2050

Achieve automation in agriculture, forestry and aquaculture industries by 2040

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