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REVIEW

Agriculture in the Semi-Arid Tropics with Sustainable Use of Scarce Resources: Contribution of Japanese Scientists through Collaboration with ICRISAT

Satoshi TOBITA[1,2]*

[1] Environment and Natural Resource Management Program, Japan International Research Center for Agricultural Sciences, Tsukuba, Japan
[2] Present address: College of Bioresource Sciences, Nihon University, Fujisawa, Japan

Abstract

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is one of 15 CGIAR centers and takes part in agricultural research and development in the most marginal regions of the world. Over the past 40 years, many Japanese scientists/projects have worked towards the improvement of crop production and betterment of livelihoods in the semi-arid tropics in both in Asia and Africa, some of which were supported by the Japanese Government and/or implemented by Japan International Research Center for Agricultural Sciences. In this paper, we review the significant scientific contributions of Japanese scientists to ICRISAT's goals for each grand research theme.

Discipline: Crop Science
Additional key words: Cereals, cropping system, natural resources, plant nutrition, pulses, soil fertility

Introduction

CGIAR celebrates its golden jubilee in 2021, while it is undergoing a major transition into a more cohesive entity. For this occasion, I review the work of Japanese scientists over the past 40 years at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), a CGIAR Research Center.

ICRISAT was established in 1972, a year after the founding of CGIAR, to conduct research on the enhanced sustainable production of food crops in semi-arid tropics (SAT). The SAT is spread over 6.5 million square kilometers in 55 countries of Africa and Asia with more than 2 billion people (Fig. 1), around 40% of whom are said to suffer from poverty and childhood malnutrition. ICRISAT's mandate crops – grain legumes (chickpea, groundnut/peanut, and pigeon pea) and dryland cereals (sorghum, pearl millet, and small millets including finger millet) – are resilient crops essential for food and nutritional security and livelihoods of the increasing populations in the SAT. For nearly half a century, ICRISAT has been working to enhance crop production and improve the management of limited natural resources. The Government of Japan (GoJ), since joining in the CGIAR in 1972, has consistently been represented in the ICRISAT Governing Board from 1976 to 2008.

In its Strategic Plan to 2020, formulated in 2010, ICRISAT states that it strives to achieve the following development outcomes: (1) food sufficiency from grain legumes and dryland cereals, (2) intensification of sustainable crop production systems, (3) diversification of crops and products for smallholder value gains, (4) resilience of smallholders maintaining food, nutritional, and economic security, (5) health and nutrition of smallholder households with more nutritious and safer diets, and (6) women empowerment through their engagement in the Inclusive Market-Oriented Development approach.

Initial collaborations

Collaborative research with Japan was established when in 1976, Japan Tropical Agriculture Research Center (TARC), the former body of Japan International Research Center for Agricultural Sciences (JIRCAS), sent Dr. Norio Iizuka, a virologist, to the ICRISAT headquarters (HQ) in Patancheru, Telangana, India. From 1977–79, he worked

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*Corresponding author: tobita.satoshi@nihon-u.ac.jp

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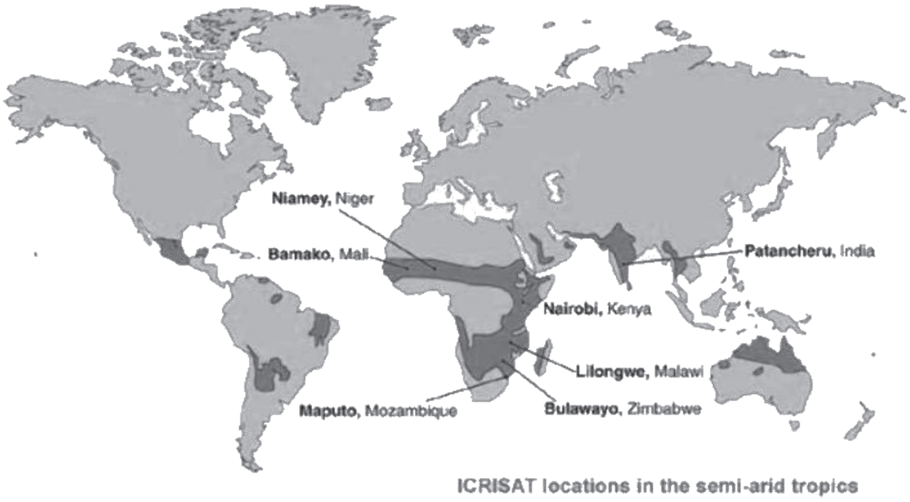

Fig. 1. Semi-arid tropics (SAT) over the world with ICRISAT headquarters at Patancheru, India, and regional hubs in Africa. (ICRISAT, 2010)

as a long-term overseas researcher of TARC to ICRISAT HQ on groundnut (*Arachis hypogaea* L.) viruses such as Indian peanut clump widely present in Punjab, northern India. Dr. Takeshi Omori became the second long-term scientist from TARC to work in Patancheru on sorghum (*Sorghum bicolor* (L.) Moench.) breeding from 1980 to 1982. Subsequently, from the National Food Research Institute, Japan, Drs. Kenji Tanaka (1981–82) and Michihiko Saito (1982–83) were dispatched to collaborate on the infection of *Aspergillus flavus* in groundnut seeds in the field, which caused aflatoxin contamination of peanuts and its products, one of the most prioritized research targets of ICRISAT at that time. In addition to the TARC scientists, ICRISAT-HQ hosted a Japan International Cooperation Agency (JICA) expert specialized in agricultural machinery, Dr. Takashi Takenaga, in the early the 1980s, who worked for mechanization and safety guides for chemical sprayers.

Apart from TARC and JICA, in this initial phase of Japan and ICRISAT, Dr. Kazumi Maeda of Kochi University stayed in Patancheru and worked for groundnut physiology and agronomy from 1978 to 1980, and Dr. Hiroshi Hirata of Tokyo University of Agriculture and Technology (TUAT) studied about phosphorus (P) availability in Alfisol and Vertisol, two soil types existing in the Patancheru field from 1979 to 1981.

Fifteen years of collaboration under the support of the GoJ

This great epoch accelerated the relationship between ICRISAT and Japan when Mr. Tsutomu Hata and Mr. Taichiro Ohkawara, Diet members of GoJ, visited ICRISAT-HQ. Subsequently, the GoJ decided to launch a restricted fund project from November 1984 with ICRISAT for special agendas that were mutually agreed upon. Since then until 1999, a series of 'GoJ Special Projects' have been implemented at ICRISAT-HQ with personnel support from TARC/JIRCAS and other agriculture research institutions in Japan. The overall mission and focus of the GoJ Projects were to conduct basic and strategic research aimed at improving nutrient and water uptake and utilization efficiencies of ICRISAT mandate crops in resource-scarce semi-arid or dry environments through field management practices and/or exploiting crop morphological and physio-genetic systems. The research themes of the three phases in the GoJ-supported projects are as follows:

1. Phosphorus nutrition of grain legumes in the SAT: GoJ Phase I (1984–89)

Alfisol and Vertisol are soils that occupy the major land areas in the SAT. People of the SAT rely heavily on these soils to support regional food needs, but they are naturally deprived of nutrients, such as phosphorus (P) and nitrogen (N). The team of Phase I scientists consisting of Drs. Noriharu Ae (leader), Joji Arihara (with experience in ICRISAT before), and Kensuke Okada (post-doctoral fellow), made careful field observations and were interested in the fact that pigeonpea (*Cajanus cajan* (L.) Millsp.) plants could grow better than other crops in alfisols, which contain high amounts of iron (Fe)-bound P, which is normally unavailable to plants. They demonstrated the unique ability of the pigeonpea to exploit and uptake the sparsely available P in alfisols. First, they developed appropriate soil test methodologies for P levels that accurately predict the P uptake and growth responses of legumes. They concluded that acidification

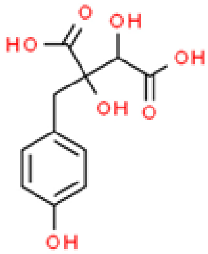

Fig. 2. Piscidic acid

of rhizosphere soil is an important factor to estimate the P uptake and analyzed the composition of root exudates by pigeon pea at different stages of growth, as along with other crops such as chickpea (*Cicer arietinum* L.) and soybean. Root exudates of pigeon pea were found to contain piscidic acid (Fig. 2), which is unique to solubilize Fe-P and release P into the rhizosphere by forming a chelating complex with P (Ae et al. 1990). This finding was expected to endow a plant with enhanced P utilization through genetic manipulation as per the known chemical mechanism in the soils.

The Phase I project had insights into the benefits of intercropping, which is commonly seen as indigenous practice in the SAT in India. The effects of P application and soil moisture on the root development of SAT crops were observed. Among them, pigeon pea was found to have deep rooting ability to facilitate the uptake of soil water and absorb nutrients from deeper soil layers rather than shallow plow layers. Therefore, scientists hypothesized that when pigeonpea is intercropped with other crops such as Poaceae, these component crops may compete less with each other for but may share a limited amount of underground resources. This triggered ideas for the Phase II project.

2. Roots and N in cropping systems of the SAT: GoJ Phase II (1989–94)

Led by Dr. Osamu Ito (later assigned as a Governing Board member to ICRISAT from 2002 to 2008), the GoJ Phase II project commenced in 1989 with Dr. Ryoichi Matsunaga (later assigned as the team leader of the JIRCAS project with the ICRISAT Sahelian Center), Katsuyuki Katayama, Satoshi Tobita (PDF until 1992), and Joseph J. Adu-Gyamfi (PDF from 1992). They focused on the hidden and hard-to-measure underground interaction of roots and nutrients between the component crops of the intercropping systems (Fig.3). To tackle these difficulties, new devices, such as minirhizotron (underground camera, Fig.4) with image analysis to observe the spatial and temporal growth of roots without being dug up or damaged by conventional methods, were introduced. They also used stable isotope N (^{15}N) to elucidate and quantify the N budget in intercropping systems, as well as a non-destructive soil solution sampling method using a ceramic porous cup by suction.

Fig. 3. Sorghum/pigeonpea intercropping at maturity in a farmers' field near Patancheru, Telangana, India.

Fig. 4. Minirhizotron observation of roots of groundnut in a Vertisol field of ICRISAT-Patancheru.

There have been significant research outputs by the team, especially on the relationship between root behavior and N flow in pigeonpea-based cropping systems. The root system model was developed with soil properties, crop characteristics, and climate data (Devi et al. 1996) to help envisage the temporal changes in roots under varying environmental conditions. The model simulated rooting profiles of the SAT cereals and legumes. Among these, pigeonpea was shown to exhibit the characteristic behavior of deeper rooting and nutrient uptake (Katayama et al. 1999). Regarding resource utilization in intercropping systems in the SAT, the N budget of the component crops and N balance sheet of the entire system of sorghum and pigeonpea intercropping were calculated using the combination of ^{15}N dilution method for N derived from fertilizer and ^{15}N natural abundance method for N derived from the atmosphere through biological nitrogen fixation. It was found that intercropping with sorghum enhanced N fixation by pigeonpea, and N fertilizer application to the system reduced the dependency of pigeonpea on atmospheric N (Tobita et al. 1994).

3. Food security in nutrient-stressed environments: exploiting genetic capabilities of plants: GoJ Phase III (1995–99)

During the previous phases (1984–94), much knowledge was gained on the mechanisms employed by pigeonpea, chickpea, sorghum, and pearl millet to acquire scarce nutrients (N and P) and water, as evidenced by root exudates, rooting ability, and N budgets of these crops in the cropping systems of the SAT. Scientists of the GoJ Phase III project, Dr. Hiroshi Nakano (leader until 1997), J. J. Adu-Gyamfi (PDF and leader after 1997), Takuji Nakamura, and Satoru Ishikawa (PDF), sought to investigate the link between nutrient physiology and genetics for better nutrient use efficiency of the SAT crops. They showed that novel and improved cultivars of ICRISAT mandate crops achieved substantial and sustainable yields in the fields of smallholder farmers in the SAT with low soil fertility and adverse rainfall. Therefore, many efforts have been made to identify and exploit physio-genetic systems that increase the extraction and utilization of nutrients by crops.

A series of glasshouse experiments was conducted to assess the genetic variation for the efficiency of nutrient acquisition and utilization. For adaptation to low N and P environments, the candidate mechanisms were identified; for example, translocation of photosynthates in relation to growth and yield, and root characteristics and absorption rate of nutrients (Nakamura et al. 2002) in hydroponic culture systems (Fig. 5). The former was studied using radioactive ^{14}C and the latter using ^{15}N and radioactive ^{32}P. In Phase III, the scientists revisited the outputs of the Phase I team, including the ability of pigeonpea to solubilize Fe-P in alfisol. Although pigeonpea specifically exudates citric and piscidic acids from the roots, there was no correlation between genotypic variability in the release of these carboxylic acids in low-P environment and P uptake by the plants. Studies were also conducted to examine the interaction between genotypes and soil types differing in water and nutrient availability. Response curves were drawn to select genotypes with high biomass and grain yields and other traits to adapt to low nutrient and moisture availability in SAT environments.

Fig. 5. Hydroponic culture of pigeonpea plants with controlled nutrients to observe root growth and to collect root exudates.

BNI in sorghum: a Japan-ICRISAT project

After Phase III, no GoJ project had been executed in Patancheru for a decade. However, in 2009, the Japan Ministry of Agriculture, Forestry and Fisheries again started a special funded project with ICRISAT with a new research theme, “Biological Nitrification Inhibition (BNI).” BNI is the scientific term for the ability to release compounds from plant roots to inhibit the soil nitrification process, as first reported by Japanese scientists on *Brachiaria* pasture in Colombia (Ishikawa et al. 2004). The existence of such a phenomenon was found in sorghum and root exudates of sorghum show substantial inhibitory effects on nitrification in the BNI bioassay system. However, it is necessary to confirm this novel phenomenon in the field, in not only growth chambers and glasshouses as BNI might potentially reduce N losses and pollution as mobile nitrate, and to improve N uptake and N use efficiency in sorghum and sorghum-based cropping systems.

For the preparation and implementation of the project, JIRCAS made an important contribution to the conceptualization of BNI research, addressed by Dr. Guntur V. Subbarao and Mr. Takayuki Ishikawa, and the dispatch of a long-term scientist, Dr. Takeshi Watanabe, as a team leader. Two post-doctoral scientists, Dr. Hiroshi Uchino (until 2010) and Tomohiro Kurai (from 2010) supported by the GoJ, participated in the project. They collaborated with ICRISAT scientists of the Resilient Dryland Systems Research Program under the project title, “Development of sustainable soil fertility management for sorghum and sweet sorghum through effective use of BNI,” for five years. These researchers elucidated that the N fertilizer use efficiency of sweet sorghum was as low as 13% to 40% (Uchino et al. 2015) and the optimum N application rate was 90 kg ha^{-1} by examining agronomic N use efficiency

Fig. 6. JIRCAS continues collaboration with ICRISAT on BNI research, focused on genetic elucidation of sorghum BNI with use of wider range of genetic resources including from West Africa. Research team members of the collaboration in the field of ICRISAT-HQ behind the sorghum varieties from WA.

and growth analysis parameters (Kurai et al. 2015). These findings could aid development of a new N fertilization management guideline. Although sorgoleone had been identified as a sorghum BNI compound (Tesfamariam et al. 2014), the evidence of BNI function and benefits of sweet sorghum was not clearly described in this project (Watanabe et al. 2015), and the issues were taken up by subsequent studies on environmental and genetic factors affecting sorghum BNI by a current JIRCAS project (Fig. 6) (Muranaka et al. this issue).

Enhancement of abiotic stress tolerance in tropical legumes

Dr. Junichi Kashiwagi, during the absence of GoJ projects in ICRISAT-Patancheru from 2000 to 2008, studied the physiology of drought tolerance in SAT legumes, especially chickpea. Dr. Kashiwagi started his work in ICRISAT to study the genetic variation in root traits in chickpea germplasm, which is important for tolerance to terminal drought stress (Kashiwagi et al. 2004). He actively worked with geneticists, molecular biologists, and physiologists to seek relevant traits and quantitative trait loci responsible for drought tolerance, such as root length density, water use efficiency, and carbon (C) isotope discrimination (Kashiwagi et al. 2013). He also participated in the first phase of the Generation Challenge Program (2004–08) along with other Japanese scientists to study drought and salinity tolerance in chickpea for identification of more than 20,000 associated expressed sequence tags. Collaboration between ICRISAT and Japanese institutions (Kazusa DNA Research Institute, Hokkaido University, JIRCAS, and others) was continued under Phase II of the Generation Challenge Programme (2009–13) to study the genetics/physiology of tropical legumes (Fig. 7).

Fig. 7. Visit of GCP II scientists of ICRISAT to Hokkaido Univ. in May 2010, hosted by Dr. J. Kashiwagi, who left ICRISAT in 2009.

In 2004, JIRCAS organized a workshop in Rome to commence international collaborations with ICRISAT and other CGIAR Research Centers (International Rice Research Institute (IRRI), International Center for Agricultural Research in the Dry Areas (ICARDA), International Center for Tropical Agriculture (CIAT), and International Maize and Wheat Improvement Center (CIMMYT)) to deploy the dehydration responsive element-binding (DREB) protein gene for crop improvement with enhanced tolerance to abiotic stresses such as drought, salinity, and high- and low-temperature. Groundnut was the target crop in the collaboration of JIRCAS/ICRISAT, and evidence of transgenic solutions for increased tolerance to drought has been demonstrated (Bhatnagar-Mathur et al. 2014).

Development of new technologies for the fertility improvement of sandy soils in the Sahel: JIRCAS project with the Sahelian Center, ICRISAT

The Sahel, a broad semi-arid belt from Senegal to Chad, with 250 to 500 mm of annual rainfall, is a major part of the SAT, along with slightly wetter Sudanian Savanna in West Africa (Fig. 8). The Sahel is marginal to the Great Sahara Desert; therefore, agricultural production is inherently low, unstable, and vulnerable to adverse events such as prolonged drought and outbreaks of pests and diseases. ICRISAT had its research center for the Sahel (ICRISAT Sahelian Center [ISC]) at Sadoré near Niamey, Niger (currently, the regional hub is at Bamako, Mali) to

Fig. 8. Bioclimatic zones of West Africa (after CILSS, 2016). In agroecological zoning (AEZ), the Sahel is "arid" zone.

conduct research and development for the improvement of agricultural productivity and sustainability and the livelihood of Sahelian smallholder farmers. In October 2002, the CGIAR Stakeholder Meeting held discussions on the soil fertility degradation in sub-Saharan Africa to be a major issue and called institutional actions for research and development to combat this problem. Subsequently, JIRCAS initiated a collaboration with ISC (or ICRISAT-Niamey) in 2003 with consideration of past feasible studies showing that low-fertility sandy soils of the Sahel could be maintained and improved using the Integrated Soil Fertility Management (ISFM) approach by encouraging positive C and nutrient cycles via organic matter management, promoting good agronomic practices for ensuring efficient use of scarce nutrients, introducing sustainable crop rotation or intercropping systems with legumes.

In the first phase, the project was managed by Dr. Hiroko Takagi, JIRCAS research coordinator. Thereafter, Dr. R. Matsunaga (previously a member of GoJ Phase II project) was dispatched to Niger as team leader, and Dr. Keiichi Hayashi, a PDF at ISC, joined JIRCAS as a scientist. Dr. Takagi organized the implementation team that included researchers from Kyoto University (Drs. Ueru Tanaka and Hitoshi Shinjo) and the University of Tokyo (Dr. Kensuke Okada, previously a member of the GoJ Phase I project), as well as scientists from Tropical Soil Biology and Fertility (TSBF)-CIAT and Alliance for a Green Revolution in Africa (AGRA) as scientific advisers. From 2006, Dr. S. Tobita (previously a member of the GoJ Phase II project) oversaw project management. In 2008, Dr. Hide Omae was assigned as a new team leader, and the Niger National Institute of Agricultural Research (INRAN) was enrolled in the project for more direct dissemination of research outputs to farmers. The project was conducted by post docs (Drs. Akira Kamidouzono, Satoshi Nakamura) and PhD students (Kanako Suzuki, Kenta Ikazaki, Yuko Sasaki), who all contributed to the project by achieving significant progress. Additionally, the Soil Analysis Laboratory of ISC was renovated to install an atomic absorption spectrometer and a gas chromatograph, and a technician of the laboratory was provided a short training in Japan for their use.

In the Sahel, most of the soil fertility in farmers' fields is attributed to organic matter such as household waste (recycling), animal droppings (collaring or *parcage* in French, Fig. 9), and plant residues (fallow), because chemical fertilizers are rarely applied (Hayashi et al. 2009). The chemical specification of N in the soil was examined to describe pearl millet growth and yield under different soil fertility management conditions, and it was found that

Fig. 9. Typical farmer's pearl millet field of the project site at Fakara. Crop and livestock are mixed and sharing scarce resources through collaring (or *parcage* in French), where animals are to graze crop residues and drop feces.

phosphate-buffer extractable organic N (PEON) could be the major soil N pool. A simple measurement protocol for PEON was established as an easy and reliable method for estimating soil N fertility in the Sahel (Suzuki et al. 2008). Long-term soil fertility experiments at Sadoré were continued, and the pearl millet yield and soil chemical properties were monitored. The results, along with the past data, showed that the combination of recovering crop residue and applying inorganic fertilizer most effectively increased pearl millet yield, compared with each sole amendment in a sustainable manner (Kamidohzono et al. 2006). Applying the data to the Rothamsted C model, it was also shown that annual C input of at least 0.8 tons ha^{-1} may be required to maintain soil organic C, given the climate conditions in the Sahel (Nakamura et al. 2012).

The effective utilization of biological resources for improving soil fertility was of great interest. Cowpea (*Vigna unguiculata* [L.] Walp.) is one of the most important leguminous crops for food and animal fodder (Fig. 10). In cooperation with International Institute of Tropical Agriculture (IITA) scientists, cowpea varieties in West Africa were evaluated for adaptation to the Sahelian environment, especially for grain and biomass production, uptake of nutrients (N and P), and biological N fixation (Matsunaga et al. 2008). As using fallow is an indigenous method of land and soil fertility management in the Sahel, fallow plant species were individually evaluated for their N sources and the contribution of the fallow practice to N fertility maintenance of the soil was quantified (Tobita et al. 2011).

Fig. 10. Cowpea fodder is transported by camel caravan for animal feedings in dry season (near Fakara).

The fallow band system (FBS, Fig. 11) was developed as a distinguished research output of the project, based on preliminary wind tunnel tests and observations in the fields of ISC. Natural fallow vegetation strip in fields can capture and accumulate aeolian fertility materials (coarse organic matter) during the dry season. Thus, the prevention of wind erosion and the enhancement of soil fertility is expected beside the band (Ikazaki et al. 2011). The effect of FBS on crop yields was well demonstrated in subsequent crop seasons in farmers' fields, so this almost-no-input technology was recognized to combat desertification and actively disseminated to local farmers in Niger through JICA's grassroots grants.

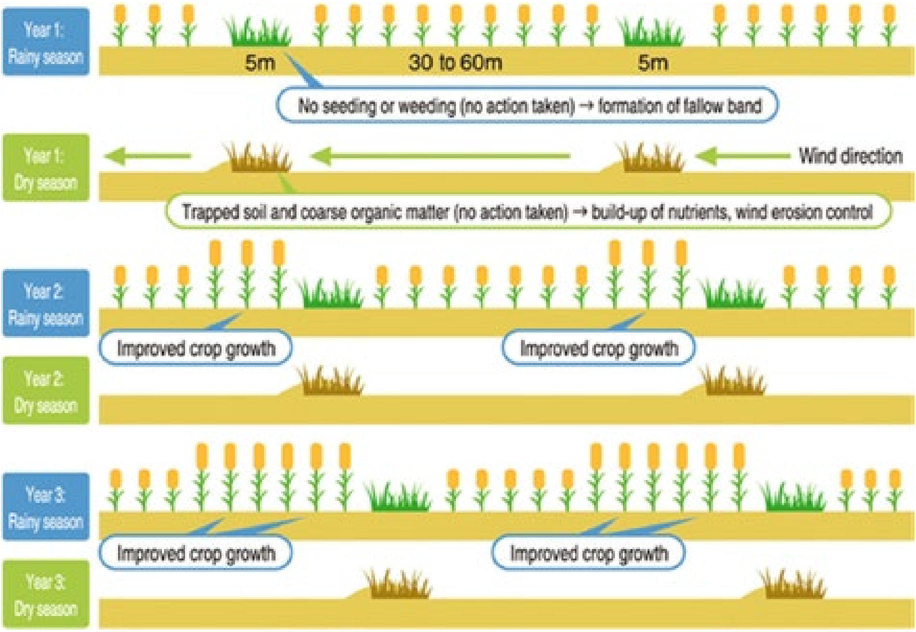

Fig. 11. Schematic description of the fallow band system (FBS), modified from Global Environmental Forum (2013).

Technologies developed by the JIRCAS-ISC project for soil fertility improvement, that is, organic matter applications and intercropping of cereals and legumes, were evaluated in on-farm participatory experiments in collaboration with INRAN in the latter phase of the project (Omae et al. 2015).

Socio-economic studies at ICRISAT-Lilongwe, Malawi

In 2015, Dr. Taku W. Tsusaka, a production economist, joined ICRISAT-Lilongwe, Malawi, a research station for SAT crops in Southern Africa. Under the CGIAR Research Program (CRP) on Policies, Institutions, and Markets, his team conducted an in-depth scoping survey on groundnut-producing smallholder farmers in Malawi and revealed that the post-harvest work was highly labor demanding. Thus, introduction of small-scale machinery for operations such as stripping and shelling was recommended. Based on this, he also published in-house reports on the post-harvest loss and ex-ante assessment of possible installment of small-scale mechanization to prevent failure and alleviate labor intensity.

Conclusions

Compared with before, the presence of Japan and Japanese scientists in ICRISAT is now small. With our limited information, no Japanese project is currently ongoing, except for the BNI research by JIRCAS. I hope that in the near future, many young Japanese scientists will understand the mission of ICRISAT and think about new collaborations in India or Africa to develop agricultural technologies for the enhancement of crop productivity in the SAT or drylands, where agricultural resources are scarce and erratic, livelihood is vulnerable to recent climate change and increasing adverse events, and the market is not yet fully engaged to local farmers.

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References

Ae, N. et al. (1990) Phosphorus uptake by pigeon pea and its role in cropping systems of the Indian subcontinent. Science, **284**, 477-480.

Bhatnagar-Mathur, P. et al. (2014) Transgenic peanut overexpressing the DREB1A transcription factor has higher yields under drought stress. Mol. Breed., **33**, 327-340.

CILSS (2016) Landscape of West Africa: A Window on a Changing World., *US Geological Survey EROS, 47914 252nd St, Garretson, SD 57030, USA.*

Devi, G. et al. (1996) Simulating root system development in short-duration pigeon pea. Expel Agric., **32**, 67-78.

Global Environmental Forum (2013) Lifestyles and measures against desertification https://www.env.go.jp/en/nature/desert/download/against%20desertification_eng.pdf. *In*, Ministry of the Environment of Japan, Tokyo, 7.

Hayashi, K. et al. (2009) Appraisal of local farmers' practices on land management for a guideline of agricultural development in the Sahel zone of Niger, West Africa. JARQ, **43**, 63-69.

ICRISAT (2010) ICRISAT strategic plan to 2020: Inclusive market-oriented development for smallholder farmers in the Tropical Drylands, *ICRISAT, Patancheru 502 324, Andhra Pradesh, India.*

Ikazaki, K. et al. (2011) 'Fallow Band System,' a land management practice for controlling desertification and improving crop production in the Sahel, West, Africa. Soil Sci. Plant Nutr., **57**, 573-586.

Ishikawa, T. et al. (2004) Suppression of nitrification and nitrous oxide emission by the tropical grass *Brachiaria humidicola*. Plant Soil, **255**, 413-419.

Kamidohzono, A. et al. (2006) Effect of long-term crop residue amendment on soil carbon and nitrogen on Psammentic Paleustalfs in the Sahel Zone, Niger. *The 4th International Conference of African Soil Society, January 7-13, 2007, Accra, Ghana.*

Kashiwagi, J. et al. (2004) Variability of root length density and its contribution to seed yield in chickpea (*Cicer arientinum* L.) under terminal drought stress. Field Crops Res., **95**, 171-181.

Kashiwagi, J. et al. (2013) Traits of relevance to improve yield under terminal drought stress in chickpea (*C. arietinum* L.). Field Crops Res., **145**, 88-95.

Katayama, K. et al. (1999) Root behavior and nitrogen balance sheet in four pigeon pea-based intercropping systems on a deep alfisol in the semi-arid tropics. Jpn. J. Trop. Agric., **43**, 181-187.

Kurai, T. et al. (2015) Efficient rate of nitrogenous fertiliser for irrigated sweet sorghum cultivation during post-rainy season in the semi-arid tropics. Eur. J. Agron., **71**, 63-72.

Matsunaga, R. et al. (2008) Yield performance, nitrogen and phosphorus acquisition of cowpea germplasm accessions in low-fertile sandy soils in the Sahelian zone. Trop. Agric. Develop., **52**, 50-57.

Muranaka, S. et al. (2021) The CGIAR–JIRCAS partnership for sustainable food systems – rice blast differential systems and biological nitrification inhibition as examples. JARQ, *under review in this special issue.*

Nakamura, S. et al. (2012) Rothamsted carbon model reveals technical options to maintain soil organic carbon under semi-arid climate. Agron. Sustain. Dev., **32**, 865-872.

Nakamura, T. et al. (2002) Varietal differences in root growth as related to nitrogen uptake by sorghum plants in low-nitrogen environment. Plant Soil, **245**, 17-24.

Omae, H. et al. (2015) On-farm participatory evaluation of technologies for soil fertility management in the Sahel, West Africa. Open Agric. J., **9**, 21-29.

Suzuki, K. et al. (2008) Applicability of phosphate buffer extractable organic nitrogen as an indicator of available nitrogen in the sandy soils of the Sahel zone of Niger, West Africa. Soil Sci. Plant Nutr., **54**, 449-458.

Tesfamariam, T. et al. (2014) Biological nitrification in sorghum: The role of sorgoleone production. Plant Soil, **379**, 325-335.

Tobita, S. et al. (1994) Field evaluation of nitrogen fixation and N-fertilizer utilization by sorghum/pigeon pea intercropping on an alfisol in the Indian semi-arid tropics. Biol. Fertil. Soils, **17**, 241-248.

Tobita, S. et al. (2011) Identification of plant genetic resources with high potential contribution to soil fertility enhancement in the Sahel, with special interest in fallow vegetation. *In* Innovations as key to the green revolution in Africa *A. Bationo et al. (eds.),* 701-706*, DOI 10.1007/978-90-481-2543-2_71*.

Tsusaka, T.W. et al. (2016) Assessing the post-harvest constraints in smallholders' groundnut production: A survey in central Malawi. Agric. Sci. Res. J., **6**, 213-226.

Uchino, H. et al. (2015) Dynamics of fertilizer nitrogen applied to sweet sorghum (*Sorghum bicolor* (L.) Moench) in the semi-arid tropics. JARQ, **49**, 409-418.

Watanabe, T. et al. (2015) Acidification in rhizospheric soil of field-grown sorghum decreases nitrification activity. JARQ, **49**, 245-253.