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Synecological Farming for Mainstreaming Biodiversity in Smallholding Farms and Foods: Implication for Agriculture in India

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We experimented a novel system of small-scale market gardening, namely synecoculture, in the temperate zone of Japan and semi-arid tropic in Burkina Faso. Synecoculture is based on highly biodiverse mixed polyculture of crops, including underutilized and neglected species, on the basis of no-till, no-fertilizer, and no-chemical practices. Through the measurements and analyses of species diversity, vegetation surface distribution, plant-insect interactions, soil environmental variables, yield performance, food and nutrition diversity, spontaneous organization of ecosystem functions in response to the introduced diversity of plant community was revealed to be compatible with productivity and various regulation services even in marginal environment. The results provide promising possibilities for the application to smallholding agriculture in India, which could potentially recover historical loss of biodiversity and multiple regulation services such as pollination and water cycle, and contribute to resolve poverty and malnutrition, if institutional supports on the access to PGRFA and leveraging technologies were properly coordinated.

Key Words: Biodiversity, Climate change, Ecosystem functions and services, ICT, Malnutrition, PGRFA, Pollination, Small holder, Soil environment, Synecological farming

Introduction

India has harboured megadiversity of culture and ecosystems throughout the human and natural history. Surrounded by the world's highest mountains and abundant traverse of large rivers, Indian subcontinent comprises various landscape ranging over vast plain, high plateau, desert, rain forest, long coastal ecosystems, *etc*, including biodiversity hotspots. Indian population is equivalent to 17-18% of the total world population, who cohabit with important concentration of biodiversity accounting for 7-8% of the species of the world (IBP, 2017).

Despite the gifted natural resources, India has been losing the majority of its biodiversity during the modern development. Original species abundance devastatingly decreased by demographic pressure mainly from agricultural land use, and is projected to further exacerbate the extinction rate by 2050 (Alkemade *et al.*, 2009). Global propagation of conventional agriculture with synthetic fertilizer certainly saved the highest number of population from hunger, yet agricultural land conversion is triggering the 6th massive extinction in life's history that is 500-1000 times faster than natural extinction rate in vascular plants (Pereira *et al.*, 2010). The loss of fundamental diversity of species provokes multiple vicious cycles in social-ecological systems. For example, India is vastly covered by the regions with serious loss of pollination service negatively impacting market output (Potts *et al.*, 2016), which highly coincides with global correlates of emerging infectious diseases (Jones *et al.*, 2008). It was one of the evidential phenomena that during the 1st International Agrobiodiversity Congress on November 6-9 2016, New Delhi was shrouded in the historical record of air pollution arising from surrounding slush and burn agriculture fields, which implied cumulative loss of regulation services. Further monoculture intensification based on solely economic incentive may jeopardize fundamental life-support of farmers by multi-trophic homogeneization of already frail ecosystems (Gossner *et al.*, 2016; Soliveres *et al.*, 2016).

Not only the destruction of ecosystems but the loss of crop diversity is crucial to human health. Since the eradication of hunger by the green revolution in 1960s, the adverse effect of culture homogenization prevails as micronutrient deficiency associated with volatility risk of single crop (Pingali, 2012). Undernutrition such as protein, vitamins and minerals deficiency, and contrary overnutrition in affluent population separate the health state between incremental difference of under- and over-

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**Author for Correspondence: Email- masa_funabashi@csl.sony.co.jp* weight, resulting in the overall expansion of risk factors of non-communicable diseases (WHO, 2003; Sachdev, 2012).

Given that India will become the world's most populated country by 2022, and continue to grow through 2050, simple sector-wise mitigation measures are not sufficient to substantially cope with the developmental conflict. The entanglement of governmental regulations, farmers' economic incentives, health and ecological degradation forms multiple burdens that require comprehensive and fundamental reconstruction of agricultural activities from production to distribution.

This should take a thoroughly integrative approach following the causal structure of social-ecological organization. To secure the fundamental life-support, biodiversity mainstreaming involving other sectors than environment is essential for the premise of sustainable development (IIED, 2014). Especially for major primary industry sectors in India (*i.e.* agriculture, animal husbandry, informal forestry), the living of those population substantially depends on ecosystem services whose benefit counts up to 58% economic value compared to their GDP per capita. Ecosystem degradation is estimated to impose the replacement cost of these services that comes at a price of 200% of their GDP (TEEB, 2008).

Under the global principle of mainstreaming biodiversity, reform of social and economic sectors needs to be addressed with top-down effective promotion such as on pricing, technological leveraging and ownership investment (Haque *et al.*, 2012; Dev *et al.*, 2015), as well as bottom-up agricultural interventions beneficial to the amelioration of nutritional status and well-being of smallholders in rural population, especially women (Bhagowalia *et al.*, 2012; Chandrasekhar *et al.*, 2015; Pandey *et al.*, 2015).

The whole process needs interactive support of information sharing and education in a wide range of geographically dispersed and ecologically diverse areas, which is expected to find compatibility with recently popularizing information and communication technologies (ICT) (Haque *et al.*, 2012; Bhagowalia *et al.*, 2012; GRFAS, 2012).

This situation is not unique in India but common in other countries supported by smallholders. Especially sub-Saharan Africa and South-East Asian countries share common problems in terms of population growth, malnutrition and vulnerability to climate change. Agricultural non-CO_2 green-house gas emissions growth will be greatest in Asia and sub-Saharan Africa (EPA, 2012), which will account for 2/3 of the increase in overall food demand in 2050 (ESA, 2012).

Developed countries are also facing the reform of agricultural sector, in face of aging population and increasing burdens of non-communicable diseases. Japan's farming crisis worsened between 1995-2015 marked with a drastic halving of workers from 4 to 2 million in farming and forestry, associated with the average age increase from 59 to 66 years old (MAFF, 2015). Japan's total health expenditure is rising up to 10% of GDP in 2014, which accounts for more than 40% of the entire national budget (WHO, 2015).

These contexts call for an internationally common development of novel food production systems adapted to the problems of today's smallholders, who produce about 80% of world food, cultivate 80% of the arable land, and occupy one third to half of the world population (FIR, 2013; FAO, 2014). Common requirement and achievement need to be shared beyond local stakeholders with strong institutional support.

Based on such global perspective, synecological farming is developed as an extreme concept of mainstreaming biodiversity and *in situ*/on-farm conservation through utilization of plant genetic resources, which has been experimented in Japan and Burkina Faso (Funabashi, 2016a; Funabashi, 2016b; Tindano and Funabashi, 2017). Initial achievement fits well to the requirement of sustainable and conservation farming in Indian context, in terms of cost reduction and profit maximization under weak infrastructure in marginal environment (Bhagowalia *et al.*, 2012; Aryal *et al.*, 2014).

In light of expansion to the largest small-holding country, this article reports the preliminary results of experiments in Japan and Burkina Faso and discuss fundamental requirement necessary for synergistic application in India, with expectation to contribute to the improvement on the international strategy of plant genetic resource conservation through active exchange and utilization with ICT support.

Materials and Methods

Synecological Farming

Synecological farming, or synecoculture in short, is based on highly biodiverse mixed polyculture of crops, including underutilized and neglected species, on the basis of no-till, no-fertilizer, and no-chemical practices (Funabashi, 2016b). Spontaneous organization of ecosystem functions in response to the diversity of plant community was a major hypothesis that was expected to be compatible with productivity and various regulation services. It was developed in Japan based on the integrated theory of physiological and ecological optima (IMPEO) that converged agronomy and ecology under a unified framework of plant science (Funabashi, 2016a). It has also recently been experimented in Burkina Faso in semi-arid tropical condition (Tindano and Funabashi, 2017). We monitored between 2010-2016 on 3000 m^2 in Japan, and 2015-2016 on 500 m^2 in Burkina Faso, a mixture of 150-300 edible species in each plot. Measurements of vegetation surface, species diversity, soil environmental variables, products diversity, and record of harvest were performed, as detailed in the following sections:

Measurement of Vegetation Surface

We developed the 2-step visual analog scale method (2-step VAS) for quick and reliable on-site measurement of species-wise covering surface of complex vegetation during initial stage of succession in synecoculture. The visual analog scale method (VAS) is a continuous psychometric response scale used in questionnaires (Grant *et al.*, 1999). The 1st step of 2-step VAS consists of 10 fixed point scaling as a preliminary step of VAS. Each observer evaluates the surface ratio of a plant species in confined area of about 2 m^2 with 10 degrees, from 1 to 10 representing 0-10% to 90-100% of the total surface, respectively. At least 3 persons evaluate independently with 10 discrete scale, and select the final scale by a majority vote.

In the 2nd step, usual VAS method is applied based on the restriction of 10 discrete scale, *i.e.* choose from 0-10% if the 1st step score is 1, from 10-20% if the 1st step is 2,… and from 90-100% if the 1st step is 10. Final VAS score of the 2nd step takes the mean value of all observers and is normalized to percentage with respect to the estimated surface of all species.

Although 2-step VAS method is based on subjective evaluation, it shows sufficient accuracy and reproducibility for the measurement of complex surface patterns following power law. Based on the evaluation with artificially generated sample pictures, the measurement error of 2-step VAS weighted by true surface ratio is confined within linear scale in double-logarithmic plot, which means that the measurement error has a scale-free property that does not affect the fitting with power function. This conforms to the characteristic of human visual perception known as Weber-Fechner law. In fact, after just a few times of practice, all observers came into perfect agreement of the 1st step of 2-step VAS, which strongly implies that the accuracy and reproducibility of the measurement depends on universal faculty of visual perception rather than trained capacity.

We measured the species-wise surface ratio of introduced crops in synecoculture field during the 1st year of succession from January to August 2011 on 300 m^2 in Oiso, Kanagawa, Japan with the use of 2-step VAS method.

For a comparison with natural vegetation, we also analyzed image data of natural vegetation in Nakagawa, Ashigara in the same region of Kanagawa, obtained from Biodiversity Centre of Japan (BCJ, 2017). Surface measurement was digitally performed with the use of Adobe Photoshop CS5, by segmenting 38 vegetation types classified by different colors in the database. Surface ratio was normalized with respect to the total surface.

Estimation of Plant-Insect Interactions

We predicted the primary interaction between plant and insect species. Based on the biodiversity record of 10 synecoculture fields in Japan along with the observation of surrounding environment and conventional plots, typical vegetation was modeled with 25 common plant species ranging over 20 taxonomical families. The list of the species and representative surface ratio is listed in Table 1.

Insect fauna of primary consumers was predicted based on the actual observation and literature in terms of plant-host relationship (Umeya and Okada, 2003). Only insects that live on direct interaction with listed plants were counted, such as eating of roots, stems, leaves, flowers, fruits and seeds. The predicted primary insect fauna is listed in Table 2. The results are depicted in Fig. 3 with the use of software R (R Core Team, 2015) for the histogram and Gephi (Bastian *et al.*, 2009) for the network representation.

Table 1. Typical vegetation of synecoculture field and conventional monoculture market gardening in Japan. Representative common vegetation of 10 synecoculture fields in Japan was extracted with typical surface ratio (50% of introduced vegetables; 20% of introduced fruit trees; 30% of naturally occurring plants; equally divided among species). Monoculture vegetation is based on 90% single *Brassicaceae* crop and 10% common weeds.

Vegetation Type	Family	Species	Typical Surface Ratio in Synecoculture	Typical Surface Ratio in Monoculture
Introduced Vegetable	Malvaceae	*Malva verticillata* var. *crispa*	0.05	
	Chenopodioideae	*Spinacia oleracea*	0.05	
	Brassicaceae	*Brassica rapa* L. var. *rapa*	0.05	0.9
	Cucurbitaceae	*Cucurbita* L.	0.05	
	Asteraceae	*Lactuca sativa* L.	0.05	
	Araceae	*Colocasia esculenta* (L.) Schott	0.05	
	Lamiaceae	*Ocimum basilicum* L.	0.05	
	Apiaceae	*Daucus carota* subsp. *sativus* (Hoffm.) Arcang.	0.05	
	Solanaceae	*Solanum lycopersicum* L., 1753	0.05	
	Fabaceae	*Phaseolus vulgaris* L.	0.05	
Introduced Fruit Tree	Ebenaceae	*Diospyros kaki* Thunb.	0.04	
	Moraceae	*Ficus carica* L. (1753)	0.04	
	Rosaceae	*Malus pumila* Mill.	0.04	
	Vitaceae	*Vitis labrusca* L.	0.04	
	Rutaceae	*Citrus unshiu* (Swingle) Marcow.	0.04	
Spontaneous Species (Common family with introduced species)	Brassicaceae	*Capsella bursa-pastoris* (L.) Medik.	0.03	0.01
	Asteraceae	*Artemisia indica* Willd. var. *maximowiczii* (Nakai) H. Hara	0.03	0.01
	Solanaceae	*Solanum nigrum* L.	0.03	0.01
	Rosaceae	*Rubus hirsutus* Thunb.	0.03	0.01
	Fabaceae	*Pueraria lobata* (Willd.) Ohwi (1947)	0.03	0.01
Other Spontaneous Species	Poaceae	*Eleusine indica* (L.) Gaertn.	0.03	0.01
	Oxalidaceae	*Oxalis corniculata* L.	0.03	0.01
	Polygonaceae	*Rumex acetosa* L.	0.03	0.01
	Equisetaceae	*Equisetum arvense* L.	0.03	0.01
	Convolvulaceae	*Calystegia japonica* (Thunb.) Choisy	0.03	0.01
Total Number	20	25	1	1

Measurement of Species Diversity and Soil Environmental Variables

We experimented biodiversity response of soil environmental variables associated with synecoculture practice with the use of 250 m^2 plot in Tokyo, Japan. After uniform introduction of silty loam soil according to USDA classification (USDA, 1993), more than 173 edible plant species were randomly introduced and vegetation was self-organized during 4 years (April 2011- March 2015) following the rule of synecoculture (Funabashi *et al.*, 2015). We allocated 36 monitoring circles of 2m diameter regularly over the plot during 3 months (April-June 2015), which were divided into 3 different management strategies A, B, and C. In A: Cut off above-ground part of naturally occurring species; B: Leave the vegetation untouched; and C: Actively introduce seeds of edible herbaceous species. Each of A, B, C group contained 12 monitoring circles. The classification was judged with 4 years of management experience that A: Needs to cut off weeds to protect edible species; C: Achieves high survival rate of newly introduced crops without weed control; B: Situation in between A and C.

We measured plant species diversity before and after the experiment, and basic soil variables at the last of experiment from all monitoring spots as listed in Table 3. Plant species diversity was obtained as the mean value of 3 independent observations. At the last stage of experiment (June 27, 2015), 76 plant species could be recognized above the ground level. Plant species were categorized into introduced and spontaneous species by the way of introduction. Herbaceous and woody species were separately counted from monitoring circles of 1m and 2m diameter, respectively.

All soil variables were measured on 3 samples and mean value for each of 36 spots was recorded. Volumetric water content of soil was measured with 3 different conditions of soil moisture during 3 consecutive days, from field capacity (pF 1.8) on the 1st day followed by 14.5 mm precipitation before the measurement of 2nd day, and further 2mm rainfall before the 3rd day.

Table 2. List of insect fauna in primary food chain. Insects that live on direct feeding relationship of plant species in Table 1 are predicted based on the actual observation record. Only insect species that depend essentially on the modeled vegetation is counted, while broader generalist species that can live on other vegetation and secondary consumers are omitted, based on the literature (Umeya and Okada, 2003). Pollination effect (P.E.) is ranked with 0: no or little pollination effect; 1: intermediate and local pollination effect such as *Coleoptera* and *Hemiptera* species (beetles and shield bugs) with infrequent flying activity; 2: High pollination effect such as *Lepidoptera*, *Diptera* and *Hymenoptera* species (butterflies, flies and bees) with high flying ability.

Order		*Acherontia lachesis*	0	Hemiptera		*Toxoptera citricidus*	0
		Acosmeryx castanea	2	*Eurydema rugosa*	1	*Unaspis yanonensis*	0
Species	P.E.	*Marumba gaschkewitschii echephron*	2	*Eurydema dominulus*	1	*Dialeurodes citri*	0
Lepidoptera		*Coleoptera*		*Graphosoma rubrolineatum*	1	*Orthoptera*	
Papilio xuthus	2	*Anomala rufocuprea*	1	*Halyomorpha halys*	1	*Chorthippus biguttulus*	0
Papilio machaon	2	*Popillia japonica*	1	*Dolycoris baccarum*	1	*Oedaleus infernalis*	0
Pieris rapae	2	*Blitopertha orientalis*	1	*Megacopta punctatissima*	1	*Locusta migratoria*	0
Colias erate	2	*Maladera orientalis*	1	*Acanthocoris sordidus*	1	*Acrida cinerea*	0
Eurema mandarina	2	*Anomala cuprea*	1	*Nezara viridula*	1	*Atractomorpha lata*	0
Pseudozizeeria maha	2	*Anomala albopilosa*	1	*Yemma exilis*	1	*Tetrigidae spp.*	0
Lycaena phlaeas	2	*Melolontha japonica*	1	*Aelia fieberi*	1	*Oxya yezoensis*	0
Lampides boeticus	2	*Gametis jucunda*	2	*Eysarcoris ventralis*	1	*Patanga japonica*	0
Vanessa cardui	2	*Epilachna vigintioctopunctata*	1	*Eysarcoris annamita*	1	*Teleogryllus emma*	0
Mycalesis gotama	0	*Anoplophora malasiaca*	1	*Nysius plebeius*	1	*Truljalia hibinonis*	0
Parnara guttata	2	*Oberea japonica*	1	*Leptocorisa chinensis*	1	*Tettigonia orientalis*	0
Bombyx mandarina	0	*Nupserha marginella*	1	*Riptortus pedestris*	1	*Euconocephalus thunbergi*	0
Spilosoma lubricipeda	2	*Phytoecia rufiventris*	1	*Hygia opaca*	1	*Phaneroptera falcata*	0
Amata fortunei	2	*Xylotrechus chinensis*	1	*Homoeocerus unipunctatus*	1	*Conocephalus chinensis*	0
Plutella xylostella	2	*Buprestidae spp.*	1	*Rhopalus maculatus*	1	*Hymenoptera*	
Tebenna micalis	2	*Paederus fuscipes*	1	*Cletus punctiger*	1	*Allantus luctifer*	0
Scythris sinensis	2	*Gastrophysa atrocyanea*	1	*Piocoris varius*	1	*Athalia* spp.	0
Bedellia somnulentella	2	*Aulacophora femoralis*	1	*Paraparomius lateralis*	1	*Dolerus* spp.	0
Ascotis selenaria cretacea	2	*Aulacophora nigripennis*	1	*Paraeucosmetus pallicornis*	1	Diptera	
Orthonama obstipata	2	*Atrachya menetriesi*	1	*Macroscytus japonensis*	1	*Delia platura*	2
Spoladea recurvalis	2	*Monolepta dichroa*	1	*Apolygus lucorum*	1	*Chromatomyia horticola*	2
Hellulla undalis	2	*Pyrrhalta semifulva*	1	*Creontiades coloripes*	1	*Rivellia nigricans*	2
Pyrausta panopealis	2	*Chrysolina aurichalcea*	1	*Adelphocoris reicheli*	1	*Rivellia apicalis*	2
Rivula sericealis	2	*Gallerucella vitticollis*	1	*Corythucha marmorata*	0	*Nephrotoma virgata*	1
Cucullia fraterna	2	*Fleutiauxia armata*	1	*Stephanitis nashi*	0	*Tipula aino*	1
Helicoverpa armigera armigera	2	*Cassida nebulosa*	1	*Graptopsaltria nigrofuscata*	0	Thysanoptera	
Spodoptera litura	2	*Cryptocephalus approximatus*	1	*Platypleura kaempferi*	0	*Thripidae* spp.	1
Agrotis segetum	2	*Basilepta fulvipes*	1	*Geisha distinctissima*	0	Dermaptera	
Mamestra brassicae	2	*Scelodonta lewisii*	1	*Ledra auditura*	0	*Gonolabis marginalis*	0
Xylena fumosa	2	*Phaedon brassicae*	1	*Aphrophora intermedia*	0	Class other than Insecta	
Oraesia excavata	0	*Psylliodes punctifrons*	1	*Cicadella viridis*	0		
Viminia rumicis	2	*Phyllotreta striolata*	1	*Episyrphus balteatus*	0	Isopoda	
Triaena intermedia	2	*Bruchus rufimanus*	1	*Myzus persicae*	0	*Armadillidium vulgare*	0
Spirama helicina	2	*Ceuthorhynchidius albosuturalis*	1	*Aphis gossypii*	0	Pulmonata	
Nokona regalis	2	*Listroderes costirostris*	1	*Aphis craccivora*	0	*Gastropoda* spp.	0
Sphrageidus similis	0	*Hypera postica*	1	*Uroleucon formosanum*	0	Total Number of Species	150
Theretra oldenlandiae	2	*Scepticus* spp.	1	*Rhopalosiphum padi*	0		
Agrius convolvuli	2	*Anthrenus verbasci*	2	*Aphis spiraecola*	0		

Harvest Record

Synecoculture produce was sold in market by Sakura Shizenjuku Co. in Ise, Japan (Funabashi, 2016b) and Agence de Formation du Développement Rural Autogéré (AFIDRA) in Burkina Faso (Tindano and Funabashi, 2017). Products were sold on-farm and *via* home delivery service in Japan, and local market at Mahadaga situated in the province of la Tapoa in Burkina Faso. High

Table 3. Measurement methods of biodiversity and soil environmental variables

Variable	Species diversity of introduced/spontaneous plant species and insect species	Soil hardness	Soil permeability	Volumetric water content of soil	Soil microbial diversity and activity	Decomposition of organic matters
Method/ Instrument	Visual Observation, photographic record	Soil hardness tester No. 351	DIK-4012 Permeameter, 4 fold type	Test method for water content of soils	Soil microbial diversity * vitality value	Tea bag index, k and S values
Reference	(Funabashi, 2013a)	(Fujiwara, 2015)	(Daiki, 2015)	(JIS, 1999)	(Sakuramoto *et al*., 2010)	(Keuskamp *et al*., 2013)

quality of products allowed us to set the price higher than conventional product, about 1.5 times in Japan and 2 times in Burkina Faso.

Results and Discussion

Power-law Surface Distribution in Synecoculture and Natural Vegetation

The surface distribution of crops in synecoculture field showed long-tail distribution that followed power law with upper limit (Fig.1). This characteristic conforms to the statistical property of natural vegetation both in vegetation-wise and niche-wise segmentation (Fig. 2). Power-law of vegetation surface is known as a self-organized property of plant community growing in ecological optimum with inherent positive interactions (Scanlon *et al*., 2007), which theoretically forms the basis of community yield in synecoculture (Funabashi, 2016a). Since the power-law distribution implies successful occurrence of symbiotic gain in the development of vegetation, the results indicate that over-yielding based on symbiotic gain could be expected from the very first years of synecoculture installation. This conforms to the harvest record from another farm in Ise, Japan and first-year result of experiment in Burkina Faso (See Yield performance section). The results are also integrated in Fig. 4 as the positive link between species diversity and symbiotic effect (power law of niches).

Estimated Plant-Insect Interactions

Plant-insect interactions based on the typical vegetation (Table 1) and estimated primary consumers (Table 2) are depicted in Fig. 3. Of 150 listed insects, 30 species that account for the top 20% of herbivory interactions occupy 57% of the total in synecoculture, and 85% in monoculture field. This constitutes a long-tail distribution of host plant surface rank of insects in synecoculture

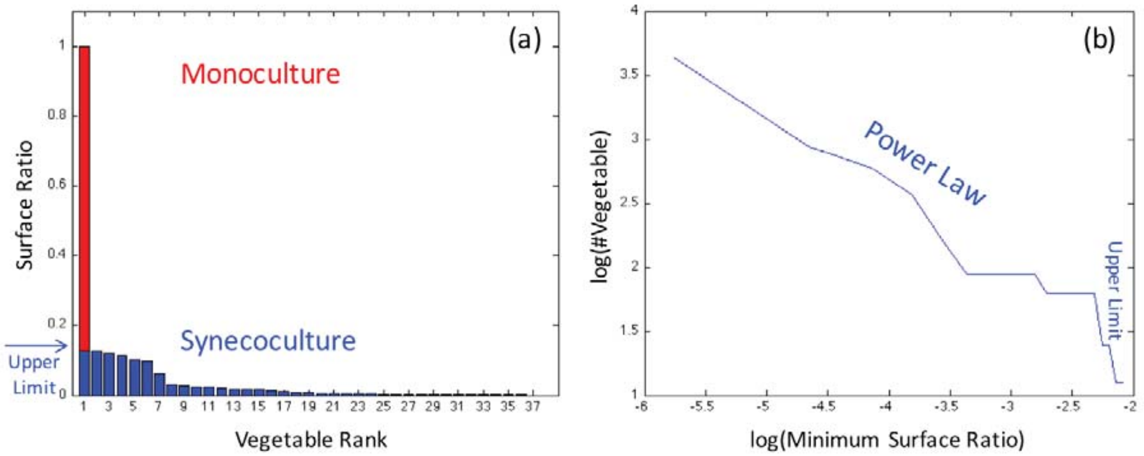

Fig. 1. Surface ratio distribution of synecoculture field in Oiso, Kanagawa, Japan based on 2-step VAS method. (a): Surface distribution of vegetables in synecoculture field (blue bars) and typical monoculture field (red bar). X-axis ranks each vegetable species according to the value of surface ratio in Y-axis. Synecoculture shows long-tail distribution with upper limit, while monoculture is confined to the growth of single crop. (b): Inverse cumulative distribution of vegetable species diversity with respect to minimum surface ratio threshold. X-axis defines the minimum threshold of surface ratio, and Y-axis represents the number of vegetable species that cover the field more than the threshold. The linear relation in double-logarithmic scale indicates a power-law distribution as a self-organized statistical property of the long-tail distribution in synecoculture.

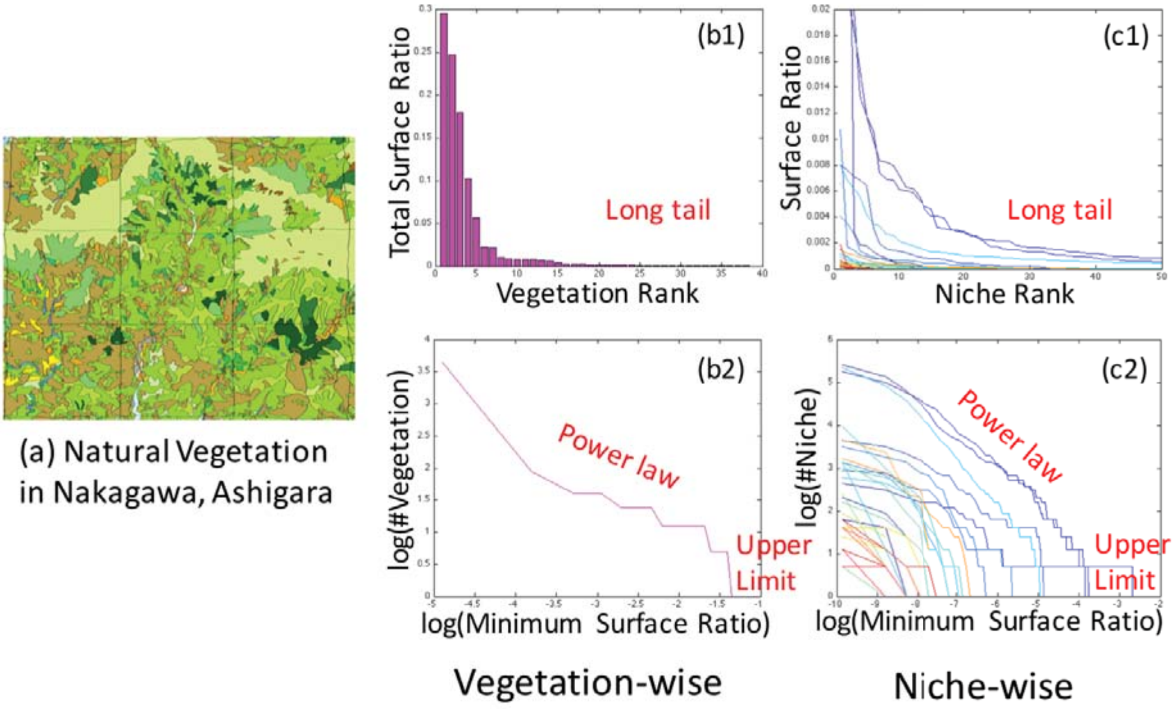

Fig. 2. Example of power-law distribution of natural niche
(a) Image data of Natural Vegetation in Nakagawa, Ashigara in Japan, from (BCJ, 2017). Vegetation types are segmented with different colors. Each segmented patch represents ecological niche of corresponding vegetation.
(b1) Total surface distribution of vegetation types. Surface ratios of segmented niches were aggregated for each vegetation. (c1): Surface distribution of niches in each vegetation. Vegetation types were distinguished with gradient colors.
For (b1) and (c1), X-axis ranks each vegetation and niche, respectively, according to the value of surface ratio in Y-axis.
(b2) Inverse cumulative distribution of vegetation type diversity with respect to minimum surface ratio threshold. (c2): Inverse cumulative distribution of niche diversity with respect to minimum surface ratio threshold. Vegetation type color corresponds to (c1).
For (b2) and (c2), X-axis defines the minimum threshold of surface ratio, and Y-axis represents the number of vegetation type and niches, respectively, that cover the field more than the threshold.
Long-tail distributions are observed in both vegetation-wise (b1) and species niche-wise (c1) surface ratio, which can be interpreted as power-law distributions with upper limit, as depicted respectively in (b2) and (c2).

[(Fig.3 (a1)], while a short-tail and discontinuous uniform distribution in monoculture [Fig.3 (b1)]. Since the host plants surface can be considered as a proxy of insect propagation rate in terms of food resources, this difference of vegetation support can be estimated to substantially affect faunal diversity and consequent ecosystem functions and services in multi-trophic levels (Gossner *et al.*, 2016; Soliveres *et al.*, 2016): Indeed, 28 insect species from the list are lost in monoculture fauna representing 19% of those harbored in synecoculture. At the same time, 96% of herbivory interactions owned by 28% of insect species essentially depend on a monoculture crop, generally considered as a pest.

Since the pest in monoculture system should be eliminated with the application of pesticides, pollination services that are included in the crop herbivory insects [Fig. 3 (b1) black bordered] are compromised in conventional farming methods. Furthermore, other pollination services of weeds owned by 72% of insect species are also subject to the elimination by weed control, which only occupy the marginal 4% of interactions that could be highly vulnerable to perturbation. Such elimination of specialist species specific to farmland is shown to further trigger a regional homogeneization of biodiversity even in case of moderate increase of land-use intensity (Gossner *et al.*, 2016).

On the other hand, synecoculture ecosystems support the community productivity and pollination services at the same time, since it complies with no chemicals practice and controlled coexistence of weeds.

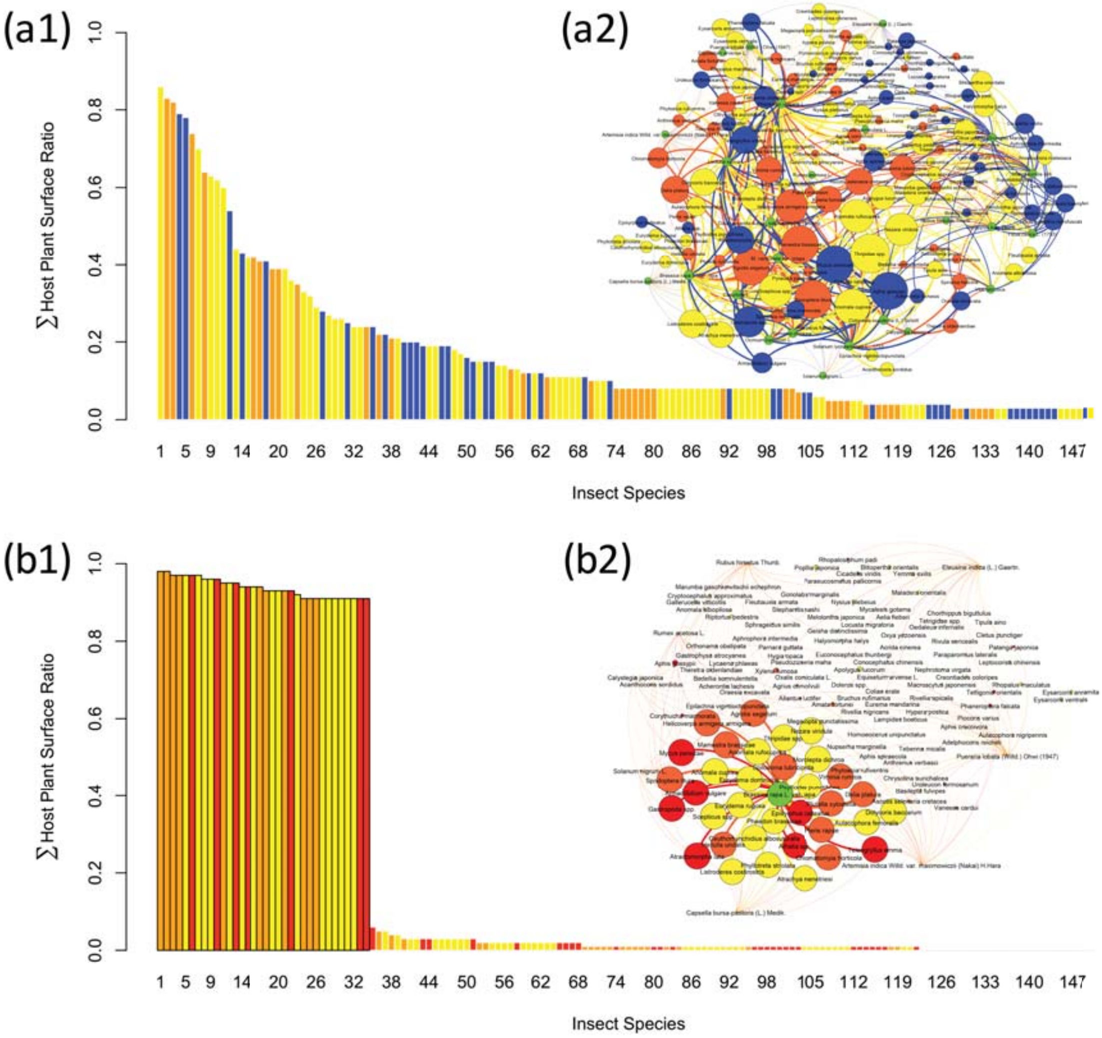

Fig. 3. Estimated plant-insect interactions in typical synecoculture (a1, a2) and monoculture fields (b1, b2).
(a1) Surface rank distribution of insect species with respect to the total surface of host plants in synecoculture.
(a2) Network representation of insect populations, host plants surface and herbivory interactions in synecoculture. The Shannon diversity of links H_2 =2.81 for all interactions, and H_2 =2.67 for pollination network.
(b1) Surface rank distribution of insect species with respect to the total surface of host plants in monoculture. Application targets of pesticide in conventional pest regulation are bordered with black.
(b2) Network representation of insect populations, host plants surface and herbivory interactions in monoculture. The Shannon diversity of links H_2 =1.73 for all interactions, and H_2 =1.62 for pollination network.
Colors represent the degree of pollination effect of insects: Red or blue (conforms to Fig. 1): 0, yellow: 1, orange: 2, and indication of plants: green. The rank of pollination effect is based on Tab. 2. The size of nodes in (a2) and (b2) refers to the surface ratio of the plants (green nodes) and total surface ratio of host plants for the insect species (red or blue, yellow, and orange nodes) that provide a proxy of propagation rate. The network edge width represents the node size of plant species.
The Shannon diversity of links H_2 decreases with higher specialization, which conforms to (Bersier *et al.*, 2002)

Out of 150 specialist species in synecoculture fields, 71% are contributing as pollinators, while 88% of 122 species as potential pollinators in monoculture system are in compromise with chemical treatment and weed suppression. This difference could project serious impact not only on crop productivity but also nutrition profile, especially micronutrients, and may results in the global increase of non-communicable and malnutrition-related diseases (Smith *et al.*, 2015).

In actually observed synecoculture fields, the overall regulation of pest was fairly achieved by the natural organization of food chain without application of chemicals. Typical realization of "diversity bugs pest" appeared commonly: On the rich diversity of primary consumers, increased diversity of predators such as spiders, wasps, mantises, ants, ladybirds, dragonflies, frogs, lizards and birds were observed (e.g. Funabashi, 2016b, p.12). These empirical evidences are expressed as the positive link between species diversity and disease and pest control in Fig. 4. Furthermore, coexistence with naturally occurring species is shown to enrich biodiversity responses of soil environment (see next section), which contributes to both productivity and pollinator diversity.

In terms of robustness, the vulnerability to perturbation can be intuitively understood with the network representation in Fig. 3 (a2) and (b2). As a general property of ecological network with competing resources, bold connections with thick nodes of multiple host plants augment the robustness and resilience of fauna in the representation of (a2), while scarce and/or thin interactions with reduced number of host plants can be easily disturbed in (b2). Especially, functional resilience of pollination is vital for the resistance of agro-environment to disturbances and can be expressed as the degree of specialization vs. generalization of network connections (Kaiser-Bunbury *et al.*, 2017). With respect to the Shannon diversity of links H_2 (Bersier *et al.*, 2002), the synecoculture network (a2) represents more generalized interactions that imply functional resilience, while monoculture case (b2) corresponds to specialization with nested and fragile structure on a single crop.

These estimations are only based on the primary consumers and do not yet include general pollinators and higher-order predators such as bees, wasps and ants important for regulation services in synecoculture, which appears as a part of the increase in net productivity (see the section Yield performance). Since the estimation is

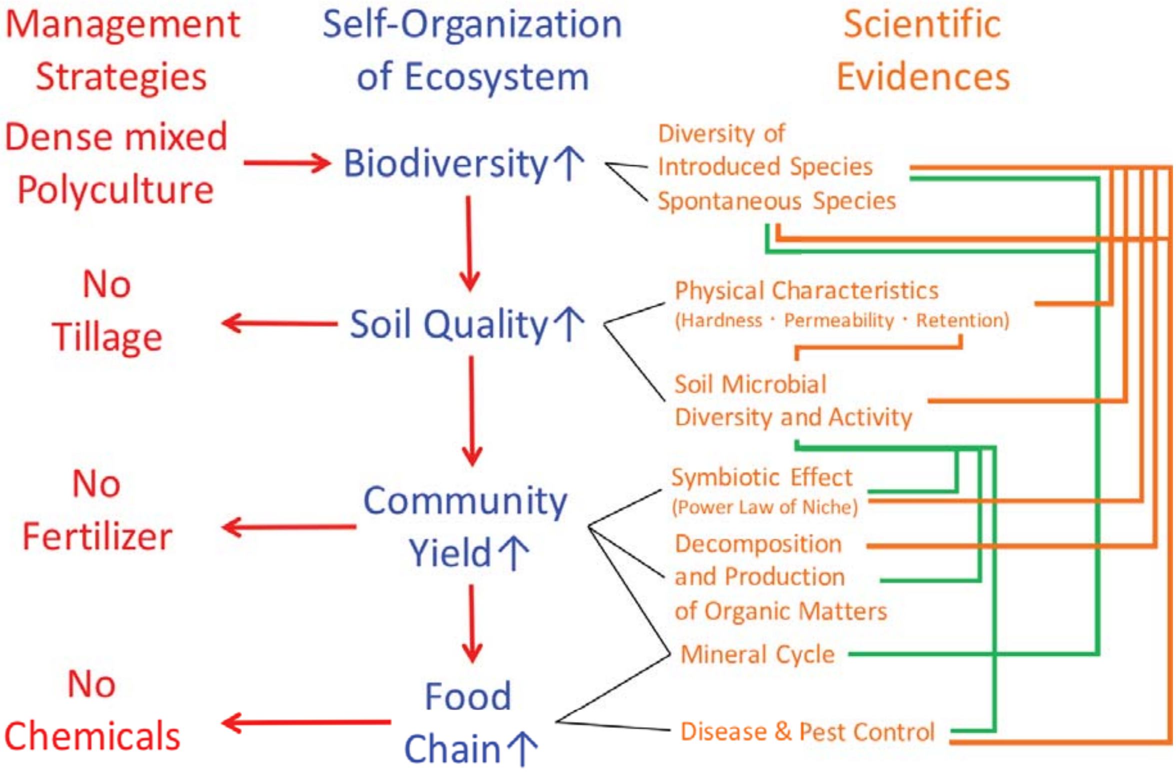

Fig. 4. Relations between management strategies (red words), self-organized properties of ecosystem (blue words), and evidences on the biodiversity responses of species diversity and soil environment (orange words). Red arrows imply consequent causal relationships in a successful development of synecoculture. Orange lines represent statistically significant correlations summarized in Table 4, while green lines show reported evidences and other general relationships associated with the measurement. Evidences in Figs. 1 and 3 are also converged. For simplicity, only direct correspondences are indicated with black lines between the self-organized properties and evidences.

based on the initial succession stage of synecoculture, it will further enrich the composition of arboreal insects that generally forms an important part of above-ground fauna. Shelter provisioning service of complex vegetation that promotes the coexistence of animal species is not considered either. Selection of the plant species is restricted to typical representative species that make up only a small part of the actually introduced diversity of vegetation.

Taking those missing aspects into account, the estimated plant-insect interactions, farming methodologies and field observations clearly indicate that the organization of food chain could be elaborated to rich introduction of natural predators and pollinators in synecoculture, and suppressed to low level in conventional monoculture.

The overall estimations provide important insights on the cause of serious loss of pollination and other regulation services in India as a consequence of conventional monoculture methods (Potts *et al.*, 2016), and how the synecoculture could recover them with the long-tail distributions of vegetation and interactions as a synergistic organization of biodiversity responses.

Biodiversity Responses of Soil Environment

Statistically significant increases and correlation between species diversity and soil environmental variables are summarized in Table 4 and schematized in Fig. 4. In brief, active introduction of edible species with high-density mixed polyculture augmented soil quality, community yield and food chain, which enabled the total replacement of tillage, usage of fertilizer and chemicals with self-organization of ecosystem functions in ecological optimum. Significant relations between evidences are as follows:

Species diversity: Active introduction of edible herbaceous species in group C showed higher establishment of species diversity including the generation of spontaneous species. Removing the above-ground part of spontaneous species (without tillage) did not negatively affect crop diversity in group A.

Soil hardness: Soil hardness after the experiment showed magnitude relation B>A>C between three groups, in which B>A and B>C are significant. Woody species diversity also contributed positively to soil hardness. This implies a trade-off between human intervention (in group A and C) and self-organization (in group B and growth of woody species).

Soil permeability: Magnitude relation A<C<B are observed. Although there exists statistically significant difference between A<B, this relation could not be explained by the difference of species diversity. Therefore, we conjecture that the human interventions affect the soil permeability more than actual species diversity, with operation A working most negatively by removing grass. Active introduction of edible species in group C seemed not to ameliorate soil permeability significantly compared to B.

Water retention ability of soil: All groups significantly increased the water content after 14.5mm of precipitation with the magnitude relation A<B<C, which were released in underground water and significantly decreased on the following day. However, only group C retained significantly higher water content after 48 hours than before the rainfall, which implied increased water retention ability by active introduction of edible species. Interestingly, high soil permeability of group B did not contradict with high water content, which may explain the compatibility of different regulation services in natural vegetation.

Increase of herbaceous and woody species diversity negatively correlated with water content. Nevertheless, since the soil contained in average 45.13% of water that is higher than 40% known as optimal value, this decrease can also be interpreted as the convergence to optimum ratio that maximizes soil function.

Further analysis on the variance of water content with F-test revealed that group A significantly decreased its variance in response to 14.5mm precipitation, indicating rapid loss of buffering capacity. These results conform to empirical facts that the loss of biodiversity negatively affect multiple regulation services of water cycle such as resilience to flood and drought.

Soil microbial diversity and activity: Soil microbial diversity*vitality values were significantly correlated with herbaceous species diversity, and became especially higher with introduced species. Woody species were positively correlated with 7.3% p-value whose edible subgroup reached 5.8% p-value (data not shown). Effects of spontaneous species were not significant and were only collateral.

Standard scores (T score) of the soil microbial diversity*vitality values with respect to 7000 soil samples from other various farming methods, crop types and regions in Japan marked 62.5, 68.9, and 72.4 for group

Table 4. Biodiversity response of soil environment in synecoculture. Results based on the measurement of species diversity and soil environmental variables analyzed with 2-sided t-tests, F-test, and Pearson's product-moment correlation. Only results of p-value lower than 5% significance level are listed. Species diversity "before" refers to the measurement before the division of monitoring sites into 3 groups A, B, and C on 28 Mar 2015, while "after" refers to the measurement after 3 months of experiment on 27 June 2015.

Biodiversity response	Variable 1	Relation	Variable 2	Statistical test	p-value
Species diversity	Group C herbaceous species diversity before	<	Group C herbaceous species diversity after	Paired t-test	0.03852
	Group B herbaceous species diversity after	<	Group C herbaceous species diversity after	t-test	0.0002604
	Group A herbaceous species diversity after	<	Group C herbaceous species diversity after	t-test	0.0002032
	Group B introduced herbaceous species diversity after	<	Group C introduced herbaceous species diversity after	t-test	9.16E-06
	Group A introduced herbaceous species diversity after	<	Group C introduced herbaceous species diversity after	t-test	5.86E-06
Soil hardness	Group A soil hardness after	<	Group B soil hardness after	t-test	0.04301
	Group B soil hardness after	>	Group C soil hardness after	t-test	0.02764
	Woody species diversity after	Positive correlation	Soil hardness	Pearson's product-moment correlation	0.04709
Soil permeability	Group A soil permeability	<	Group B soil permeability	t-test	0.01507
Water retention ability of soil	Group A water content of soil of field capacity (pF 1.8)	<	Group A water content of soil after 14.5mm precipitation in 24 hrs	Paired t-test	0.014
	Group A water content of soil after 14.5mm precipitation in 24 hrs	>	Group A water content of soil after 16.5mm precipitation in 48 hrs	Paired t-test	0.0001058
	Group B water content of soil of field capacity (pF 1.8)	<	Group B water content of soil after 14.5mm precipitation in 24 hrs	Paired t-test	0.001584
	Group B water content of soil after 14.5mm precipitation in 24 hrs	>	Group B water content of soil after 16.5mm precipitation in 48 hrs	Paired t-test	0.03147
	Group C water content of soil of field capacity (pF 1.8)	<	Group C water content of soil after 14.5mm precipitation in 24+D54 hrs	Paired t-test	0.0008536
	Group C water content of soil after 14.5mm precipitation in 24 hrs	>	Group C water content of soil after 16.5mm precipitation in 48 hrs	Paired t-test	0.02111
	Group C water content of soil of field capacity (pF 1.8)	<	Group C water content of soil after 16.5mm precipitation in 48 hrs	Paired t-test	0.0002117
	Group A water content variance of soil of field capacity (pF 1.8)	>	Group A water content variance of soil after 14.5mm precipitation in 24 hrs	F-test	0.02993
	Woody species diversity after	Negative correlation	Mean water content of soil	Pearson's product-moment correlation	0.0008532
	Introduced woody species diversity after	Negative correlation	Mean water content of soil	Pearson's product-moment correlation	6.87E-05
	Herbaceous species diversity after	Negative correlation	Mean water content of soil	Pearson's product-moment correlation	5.22E-05
	Introduced herbaceous species diversity after	Negative correlation	Mean water content of soil	Pearson's product-moment correlation	0.01601
	Spontaneous herbaceous species diversity after	Negative correlation	Mean water content of soil	Pearson's product-moment correlation	1.41E-06
Soil microbial diversity and activity	Herbaceous species diversity after	Positive correlation	Soil microbial diversity * vitality value	Pearson's product-moment correlation	0.0007458
	Introduced herbaceous species diversity after	Positive correlation	Soil microbial diversity * vitality value	Pearson's product-moment correlation	0.0006723
Decomposition and production of organic matters	Spontaneous woody species diversity after	Negative correlation	Tea bag index S value	Pearson's product-moment correlation	0.004487
	Group C tea bag index k value	Negative correlation	Group C tea bag index S value	Pearson's product-moment correlation	0.005975
	Group A soil permeability	Negative correlation	Group A tea bag index S value	Pearson's product-moment correlation	0.0021

Table 5. Harvest records of synecoculture farm in Japan and in Burkina Faso. Annual harvest is calculated in each currency based on the annual mean of the whole experiment period. Price rate refers to the pricing of synecoculture produce compared to conventional products in the market. Product species diversity describes the number of species actually sold as synecoculture products. Conventional harvest is based on (JA, 2015; Tindano and Funabashi, 2017)

Location	Surface	Period	Synecoculture Harvest	Conventional harvest	Price rate	Product species diversity
Ise, Mie prefecture, Japan	1000 m^2	June 2010 - May 2014	519,834 JPY/yr	250,000 JPY/yr	1.5	133 spp.
Mahadaga, province of la Tapoa, Burkina Faso	500 m^2	June 2015 - November 2016	7,572,000 CFA/yr	720,500 CFA/yr	2	37 spp.

A, B and C, respectively. These T scores correspond to empirical evaluation that group A: rich soil, good taste of produce, suppress diseases; group B: Very rich soil, very good taste of produce, little occurrence of diseases; and group C: Extremely rich soil, low occurrence of pest and possible to cultivate with less amount of fertilizer and less effort of weed control (DGC, 2015). The overall results could be positively linked with the effect of symbiotic gain promoted by active introduction of edible plants through the organization of ecological optimum.

Decomposition and production of organic matters: Spontaneous woody species diversity and group A soil permeability were negatively correlated with S value of tea bag index. Additionally, k and S values were negatively correlated only in group C. According to the definition, k represents short-term decomposition dynamics of labile compounds, and S is indicative for long-term carbon storage by environmental conversion to recalcitrant fraction (Keuskamp *et al*., 2013). Therefore, these results can be integrated into the hypothesis that the increased species diversity drives the material cycle of organic matters into decomposable fraction by eliminating recalcitrant stock. This dynamic conforms to the increased flow in the decomposition and production cycle of organic matters generally expected from high soil microbial diversity and activity through disease suppression (Yokoyama and Taguchi, 2013).

It is also reported that increased biodiversity is associated with the promotion of mineral cycle in synecoculture, showing high concentration in produce despite insufficiency in soil (Funabashi, 2013b). Spontaneous insect diversity is estimated to be the primary source of mineral concentration in the no-fertilizer culture environment.

Yield Performance

The summary of harvest record of 4-year (June 2010 – May 2014) and 1.5-year (June 2015-November 2016) experiments, respectively in Japan and Burkina Faso, is listed in Table 5. Compared to conventional market gardening in the same region, synecoculture result in Japan achieved about 2-fold productivity and 5-fold profitability after cost deduction (JA, 2015). In Burkina Faso, small-scale comparison on 500 m^2 in the same location attained more than 10-fold productivity and cost effectiveness with synecoculture. Furthermore, unit surface comparison with nation-wide statistics of conventional systems reached the estimation of 40 to 150-fold productivity. The outstanding performance in semi-arid tropic was also associated with a drastic recovery of local biodiversity, that reversed the local regime shift from uncultivable desert to mature vegetation composition of primary succession (Tindano and Funabashi, 2017).

Food and Nutrition Diversity of the Products

Product diversity reached 133 species from 4-year record in Japan and 37 species during 1.5 year in Burkina Faso. With nothing but 1000 and 500 m^2, respectively, these are comparable with the product diversity of regional scale and expected to largely contribute to promote food diversity with local production. Especially introduction to family garden in rural area could benefit effectively both in nutrition and generating income through utilization of neglected and underutilized species (Padulosi *et al*., 2012). Nutrition diversity of synecoculture products showed various expression of health-protective components, such as increased concentration of minerals and expression of secondary metabolites which potentially provide preventive effects on non-communicable diseases (Funabashi, 2013b; Funabashi, 2016a).

Implication for Agriculture in India

Synecoculture results out-performed conventional monoculture systems of market gardening both in the temperate region of Japan and semi-arid tropic in Burkina Faso. These results indicate promising possibilities for the introduction of synecoculture to small-holding farms and family gardens in India.

In terms of latitude and climate, India is situated at the combination of Japan and Burkina Faso: The southern halves of Karnataka and Andhra Pradesh states mainly overlap to the latitude range of Burkina Faso (Bangalore is in close latitude with Ouagadougou), and the Himachal Pradesh state in Northern India corresponds to the Kyushyu island in the South of Japan.

With respect to the Köppen-Geiger climate classification based on vegetation types (Peel *et al*., 2007), the Southern and Western halves of India commonly share the Savanna climate (Aw), hot semi-arid climate (BSh), and hot desert climate (BWh) with Burkina Faso. On the other hand, the North-Eastern part of India belongs to the Monsoon-influenced humid subtropical climate (Cwa) and subtropical highland climate with dry winters (Cwb) where results in Japan with the humid subtropical climate (Cfa) could be applied with additional consideration for water management (the abbreviations represent the Köppen-Geiger climate classification scheme symbols).

Precipitation records show that the Western half of India corresponds to below 1000 mm/year (except the rain-abundant biodiversity hotspot in the South-Western coastal area), which can employ farming strategies developed under the 800-1000 mm annual rainfall in la Tapoa province in Burkina Faso (Survey of India, 2006; PICOFA, 2006).

These geographical and eco-climatic conditions located in India together with social-ecological states of poverty, malnutrition and environmental degradation as an important target in need for a larger-scale application of synecoculture in smallholding population. Indeed, the synecoculture performance achieved in the environmental reconstruction, food security and income generation especially in semi-arid tropic and weak infrastructure conditions, could possibly help in achieving Aichi Biodiversity Targets by 2020 and the Sustainable Development Goals 2015-2030 of the United Nations (Tindano and Funabashi, 2017). Successful replication requires the adaptation and improved access and benefit sharing to commercial and local plant genetic resources (PGR).

In terms of the diversity of plant genetic resources for food and agriculture (PGRFA), synecoculture farms can be considered as a novel example of "*in situ*/on-farm conservation through utilization." The collaboration with on-going international gene bank initiatives and coordination of farmers' seed system including exchange opportunities of local varieties and neglected/underutilized species could provide essential support for the propagation of synecoculture. These are expected to largely promote the global action plans for the conservation, sustainable use, institutional and human capacity building of PGRFA and climate resilience through the implementation to smallholders (Diulgheroff and Leskien, 2016; Sthapit *et al*., 2010).

In strengthening the crop portfolio, application of the plant science to produce non-GMO (non-genetically modified organism) varieties of crops could be important in accordance with synecoculture principles. Important features for dryland agriculture such as drought resistance and low nitrogen tolerance, as well as adaptations to marginal land and climate change such as by hybridization with wild perennials and extension of photoperiodic responses, could be better enhanced with traditional breeding and phenotypic selection than transgenic technologies (Funabashi, 2016a). The principle of non-GMO is also important in terms of the genetic pollution risk to PGR that support the water cycle. The creation of GMO only introduces at most 10 kinds of gene, and it contains the risk that could bring invasive outcome to the diversity of PGR in metapopulation, not only through introgressive hybridization but also interspecies gene transfer that is prevalent in the natural evolution of plant genome. On the other hand, genetic resources that support the provisioning and regulation services of water cycles are composed of all living organisms participating to the soil formation where surface flows are buffered and groundwater nurtured. These include plant, animal, and microbial species, which amounts to astronomical figures. Incorporation of water cycles in the management of farmland becomes cumulatively important at the vast watershed of large rivers for the downstream water quantity and quality, including impacts on marine ecosystems. Enhancing PGR of the regional environment through the diversification of PGRFA could be a more comprehensive solution than GMO-based systems in dryland agriculture where the majority of Indian smallholders subsist. This perspective also encompasses the diversity of medicinal plants used in traditional medicine such as Ayurveda, which is increasing its importance as a source of scientific discovery and the foundation of healthcare (*e.g.* IFDC, 2015).

For efficient promotion of PGRFA diversity among smallholders, ICT supports with open-source initiatives are featured to be an essential infrastructure. Modern open-source intermediaries are expected to increase the capacity to handle the future and spot exchange of diverse commodities, and become important hubs for rural businesses that might contribute to market efficiency and price stability (Gulati and Minten, 2008). This could further facilitate the prediction and reduction of subsidy bill of the Government, and connect the significant gap between data and policy to enhance the nutrition sensitivity of agriculture in India (Gillespie *et al.*, 2012).

More fundamentally, the spatial-temporal patterns of biodiversity in ecological optimum follow power-law distribution (see section Power-law surface distribution in synecoculture and natural vegetation), which requires the control by information rather than material inputs. The Access and Benefit-Sharing Clearing-House mechanisms regarding the PGRFA for the implementation of Nagoya Protocol substantially requires a nation-wide ICT network for an effective real-time management.

Conclusion

We reported experimental results of synecoculture in Japan and Burkina Faso in view of application to Indian contexts. In terms of productivity, promotion of biodiversity and sustainable use of PGRFA, social and ecological problematics, India is situated at one the largest target nations that synecoculture could potentially contribute to leverage small-holding agriculture. The application of synecoculture could be expected to bring higher positive impact in marginal dryland under weak infrastructure and low income conditions, as proved in Burkina Faso.

If successful convergence to ecologically optimum production was realized in small-holders that constitutes more than half of the national and about 80% of farming population, the nation could entirely break away from historically exacerbated biodiversity losses, recover multiple regulation services that strengthen adaptations to climate change, and substantially improve food security and malnutrition. Given its scale of the surface and biodiversity, such transformation could lead India to be a major actor to prevent the global regime shift anticipated before the middle of the century, as the realization of a true megadiverse country through anthropogenic augmentation of ecosystems (Funabashi, 2016a).

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