

Chapter 1

Augmentation of Plant Genetic Diversity in Synecoculture: Theory and Practice in Temperate and Tropical Zones

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Abstract Natural vegetation forms a complex fractal structure of ecological niche distribution, in contrast to human-managed monoculture landscape. For the sustainable management of diverse plant genetic resources, including crop and wild species, the introduction of such ecologically optimum formation is important to compensate for the biodiversity loss and achieve higher ecological state that can provide sufficient ecosystem services for increasing human population. In this chapter, we first develop a conceptual and theoretical framework for the implementation and management of self-organized niche structures and develop an adaptive strategy of sustainable food production resulting from the statistical nature of ecosystem dynamics called power law. Second, we construct the integrative measures for the management of plant genetic resources for food and agriculture in ecological optimum that incorporate both phylogenetic and phase diversities as important functional indicators of plant communities. This formalization leads to the extension of conventional concepts of biodiversity and ecosystem services toward human-assisted operational ecological diversity and utility and provides the definition and property of potentially realizable and utilizable plant genetic resources in the augmented ecosystems beyond natural preservation state. Finally, case studies from the synecoculture project in temperate and tropical zones are reported in reference to the developed framework, which draws out legislative requirements for future protection and propagation of plant genetic resources. The necessity of supportive information and communication technologies is also demonstrated. This article contains theoretical foundation and the results of the proof of concept experiments that are essential to establish a novel developmental and legislative framework for the sustainable use of plant genetic resources, overarching the protection of the natural environment and agricultural production mainstreaming biodiversity.

Keywords Plant genetic resources (PGR) · Ecological optimum · Power-law distribution · Synecoculture · Anthropogenic augmentation of ecosystems ·

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Operational species diversity · Adaptive diversification · Ecological recapitulation principles · Open complex systems · Complexity measure · Information and communication technologies (ICT) · Traditional knowledge of indigenous peoples and local communities · Aichi biodiversity targets · United Nations sustainable development goals (SDGs) · The Nagoya Protocol on Access and Benefit-Sharing

1.1 Introduction

Human activities, especially agriculture, are considered to have exceeded planetary boundaries of natural resources and their cycles for the maintenance of the Earth System (ES) out of the Holocene epoch where human civilizations have developed (Steffen et al. 2016). It may lead the ES to an unprecedented shift to Anthropocene with various risks and uncertainty on the life support of the growing population (Crutzen 2002).

Among natural resources, material resources are estimated to peak and deplete around the middle of the twenty-first century, both for fossil fuels (Turner 2008) and rare metals (UNEP 2013). Not only the remained exploitable amount, but mining costs are approaching the efficiency bound. Significant parts of these material resources are non-renewable, and it is not yet technically possible to completely substitute with other resources at the level of sustaining the current rate of economic growth.

Biological resources such as biodiversity and plant genetic resources (PGR) are also incurring severe damage by the inappropriate practice of agriculture. The extinction rate of vascular plants is 500–1000 times higher than the natural background rate (Pereira et al. 2010), and the global collapse of the ecological state is anticipated (Barnosky et al. 2012).

Nevertheless, biological resources are renewable and have survived several massive extinction events during the evolution of ES (Rohde and Muller 2005). PGR itself can be considered as long-term renewable and sustainable resources that contain the self-adaptive capacity to climate change and other global forcings, whether natural or human-caused.

In responding to urgent needs for the transition to sustainable social–ecological systems, the *in situ* conservation of PGR is an essential framework both for primary food production and conservation of ecosystems (NRC 1993). It implies both on-farm and field management of PGR at the plant community level with its evolutionary context, in which there is importance on the mixed vegetation established by ecological optimum (Putman and Wratten 1984), in contrast to the physiologically controlled culture of a single crop.

Based on ecological incentives, there has been lots of attempts to partially introduce ecological optimization in farming method, such as organic farming, natural farming, and in its extreme case synecological farming (synecoculture) that totally relies on the formation of ecological optimum at the community level for the production (Funabashi 2016a, 2017a).

As the material resources are approaching its mining limit and biological diversity threatened, the in situ management of plant genetic diversity through low-input food production system becomes of primary importance for reconciling between development and sustainability. In this chapter, we first analyze the geometrical and statistical properties of plant communities realized by ecological optimum and develop a series of strategies to make use of these distributions in the context of synecoculture. Secondly, we report the results of field experiments of synecoculture in accordance with the developed theory, as a strategic augmentation of plant genetic diversity on the plots in Japan, Taiwan, and Burkina Faso, ranging over temperate and tropical zones.

1.2 Power-Law Distribution of Ecological Niches

Typical surface distribution of natural vegetation with symbiotic interaction in ecological optimum is known to follow a power law (Scanlon et al. 2007; Seuront 2010; Fariior et al. 2016), which is also observed in synecoculture (Funabashi 2017a). Here, we examine the invariant properties of the power law in naturally organized vegetation with respect to the measurement parameters, in order to build a theoretical framework for the interpretation of field data.

As a simple assumption, actual measurement of vegetation surface is confined by two parameters: total surface of measurement spot and spatial resolution of the measurement. We assume a general model of power-law distribution as Pareto distribution, whose probability density function $f(x)$ on $x > b > 0$ is defined as follows:

$$f(x) = \frac{ab^a}{x^{a+1}},$$

where $a > 0$ is the scale-free parameter of the power law.

Suppose we measure the vegetation surface with the resolution of percentage, from 1 to 100%. Then, the bottom limit of the surface x should be confined by more than 1% of the total surface, which fixes b to be 0.01 times total surface. We call this assumption as “%-measurable” property of vegetation. It means that species surface less than 1% of the total surface is ignored from the observation.

The gradient of a power law, a , varies according to vegetation types and resolution of observation. Therefore, we numerically change the value of a with respect to the total surface and examine acceptable species diversity as the number of surface divisions that follow a power-law distribution. Actually, it suffices to fix an arbitrary total surface and generate a range of a where samplings from the Pareto distribution are confined within the range of 1–100% of the total surface. Other sampling parameters that produce data with more than 100% values of total surface mean the observation scale is too small compared to the actual niche surface, which should be eliminated as an inappropriate observation. The result is shown in Fig. 1.1.

The simulation shows that the appropriate measurement of species diversity defined as the number of different partitions following power law should be situated

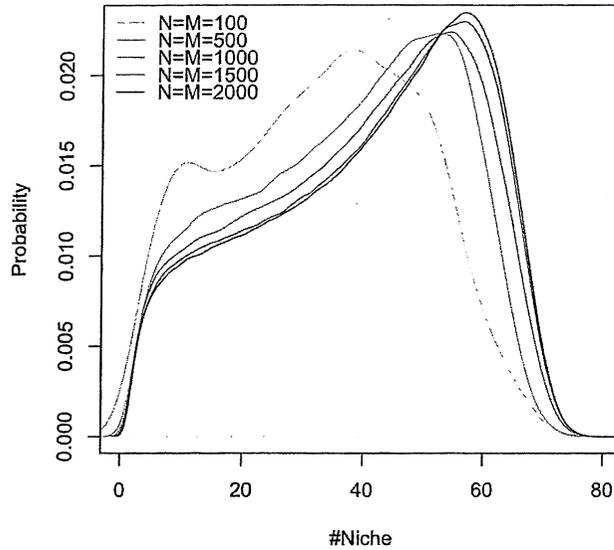


Fig. 1.1 Invariant distribution of species diversity following power-law surface distribution. As a simulation of %-measurable vegetation surface distribution, the total surface was set to 100, the parameters of Pareto distribution $b = 1$, and $0 < a \leq 3$. The range of a was divided by parameter N that ranges from 100 to 2000, which numerically encapsulated the range of %-measurable distribution. X -axis represents the number of partitions generated from Pareto distributions, which represents a maximum acceptable number of ecological niche or species diversity of plants, and Y -axis shows the estimated probability density after M times of sampling. As N and M increase, convergence to an invariant distribution is observed under random sampling assumption. All simulations and visualizations in this article were performed using R version 3.2.0 (R 2015)

somewhere between 10 and 65 species, most plausibly between 40 and 65 species, if based on the %-measurable assumption and choosing an appropriate scale with respect to actual power-law surface distribution. This model fixes the total surface and changes the characteristic parameter a , while in actual measurement we need to choose appropriate measurement scale in order to validate the count of species diversity in effective power-law range and estimate a (see Sect. 1.7).

Let us introduce another perspective on the origin of the power-law distribution in the spatial distribution of vegetation. It is known in general that a stochastic process including both additive and multiplicative noises has a property of converging to power-law distribution (Takayasu et al. 1997). Specifically, when the growth of niche surface is expressed by $p(t)$ with time parameter t , the development of niche surface distribution is expressed in discrete time as

$$p(t + 1) = GRp(t) + p'(t)$$

Here, $GR > 1$ is a stochastically fluctuating growth rate, and $p'(t)$ is a fusion with another niche of the same species. Then, since $GR > 1$ is multiplicative and $p'(t)$ is additive, the developed niche structure follows a power law.

1.3 Measuring Yield on Power-Law Vegetation

In the physiological optimization of a single crop, the average value of the environmental parameter giving the maximum production amount is fixed to a specific value. However, when niche division occurs in ecological optimization, the environmental condition giving the locally maximum amount of production could divide into two or more, with different distributional areas (Putman and Wratten 1984). In addition to the physicochemical parameters such as climate and soil conditions, other ecological parameters such as the type of competing vegetation become important in the set of environmental parameters; therefore, the parameters that define the niche condition cause a combination explosion. Assuming that there are n types of matrix vegetation that can grow under a given environmental condition, $\sum_{i=1}^k n C_i$ types of combinations arise only by selecting any set of $k \leq n$ types or less therefrom. This combinatorics defines the upper limit of possible variations of niche diversification on these crops.

Specifically, let us schematically consider the diversification of niches on the three main factors of plant growth, temperature, humidity, and amount of sunlight, with a set of countless competing vegetation. Temperature, humidity, and sunlight are defined as x -, y -, z -coordinates, respectively, and competing vegetation grows in this environment as dominant species. Now, if you add another competing vegetation so that the single niche space is divided into two for each of the x -, y -, z -axes, the remaining cultivation niche is equal to the phase structure of fractal figure called Menger sponge.¹ Indeed, it is known that vegetation in a mixed state of many species organizes a fractal arrangement (Seuront 2010), and the fractal dimension is also applied to satellite image analysis that provides the proxies of vegetation type (Nayak 2008). The modeling approaches include cellular automata (Scanlon et al. 2007) and recursive formal grammar such as Lindenmayer system (L-system) (Prusinkiewicz and Lindenmayer 2012). Rigorous mathematical analyses of the models, such as the generative mechanism of the power law and numerical convergence of geometric measures such as fractal dimension, require the functional analysis of fractal figure. In the ecologically optimized state, if we cannot handle such a complex niche structure comprehensively, we cannot discuss the yield based on the vast combination of competing crops.²

¹A concrete example in one dimension is given in Appendix 3.

²In measuring the surface on a fractal figure like Menger sponge, the usual Riemann integral is extremely difficult to handle. Originally, Riemann integral is defined based on infinite series, but a fractal figure is a function defined on the limit operation of infinite iteration of a map. Therefore, when attempting to perform Riemann integration of a fractal figure, it is necessary to calculate the "limit value of the function defined by the limit value," which becomes analytically difficult. In reality, although the actual vegetation distribution has fractal feature, the lowest resolution is fixed to a finite value in actual data, but it is still complex to analytically calculate Riemann integral of long finite series on an iterative model. Besides a simple surface area, to calculate essential characteristics of a fractal figure such as fractal dimension, one needs to be based on the measure theory such as Hausdorff measure and related numerical implementation such as the box-counting method. Furthermore, to integrate on qualitative variables contained in ecosystem data, a method of

The Lebesgue integral (or in a more general setting, measure integral) can build an integral over such a complex set.³ In the Lebesgue integral, the area and the volume of a complex set can be collectively calculated by constructing a measure on the set theory. Besides length, area, and volume, the measure can be configured as the number of events, probability, and any other objective functions. In actual data analysis, Lebesgue integration can be programmed with a database search algorithm. Even if you do not solve it analytically, you can numerically calculate the objective functions based on the search conditions. The set-theoretic operation can be replaced with computation (Funabashi 2017b).

Let us see a concrete example. In the niche division, as shown in Fig. 1.2, the region of the environmental parameter where the vegetation gives a yield equal to or more than the lower bound α is given by $X|_{Y(X) \geq \alpha}$, where X is the space of the environmental parameter, and $Y(X)$ is the average yield distribution of the vegetation. This means to choose only the set that satisfies $Y(X) \geq \alpha$ out of the subsets of X , and it does not matter how complex it is in X . If multidimensional Lebesgue measure m is constructed on X , Lebesgue integration can be performed even in case $X|_{Y(X) \geq \alpha}$, where niche(s) above the yield α is a fractal figure. Specifically, the yield $Y|_{Y \geq \alpha}$ at niches above the yield α is calculated as the Lebesgue integral

$$Y|_{Y \geq \alpha} = \int_{X|_{Y(X) \geq \alpha}} Y dm.$$

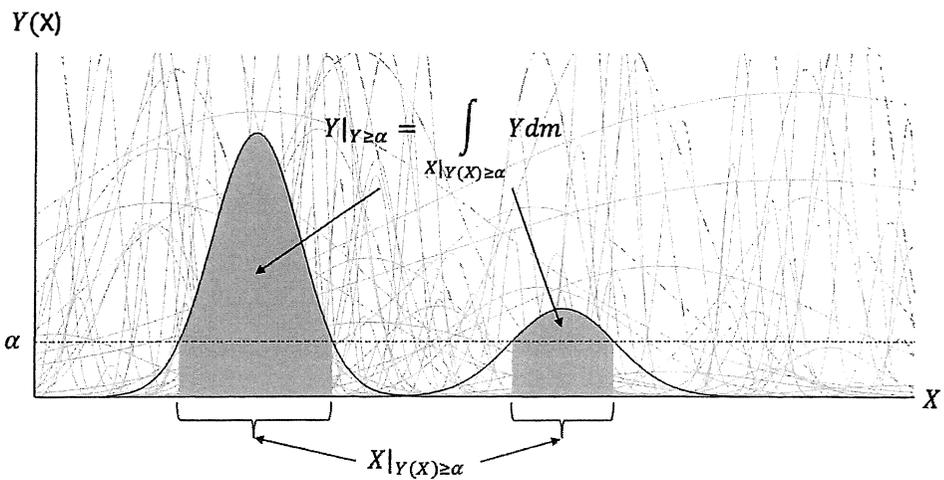


Fig. 1.2 Definition of yield on simulated examples of mixed power-law vegetation with multiple species. Examples of divided niches are depicted with the yield $Y|_{Y \geq \alpha}$ (gray area) as defined in Sect. 1.3. See Sect. 1.4 for the model description

counting qualitative variables must be set separately, which requires the formalization of measure integral.

³Basic formalization of Lebesgue integral for vegetation data is detailed in Appendix 1.

In general, the yield data such as biomass is challenging to obtain exhaustively, but the distribution map of vegetation can be more easily created from the field survey and is released from various research institutes. When dealing with a vegetation distribution map, the coverage area per vegetation can be calculated with the above formulation, if α is interpreted as a threshold for determining the presence or absence of vegetation.

In vegetation survey, when a map is prepared as a distribution site of a particular vegetation where the density $Y(X)$ is not less than α , the distribution function of the vegetation is given by the definition function $\mathbf{1}_{X|Y(X)\geq\alpha}(X)$ of the distribution area $X|Y(X)\geq\alpha$. The covering area S of the vegetation, if X is the two-dimensional coordinate of the map, is given as follows in the same way as the yield,

$$S|_{Y(X)\geq\alpha} = \int_X \mathbf{1}_{X|Y(X)\geq\alpha} dm.$$

This corresponds to the niche area of the vegetation in ecological optimum.

From this, the average yield per surface $E[Y|Y\geq\alpha]$ in niches defined by the lower bound of yield α is given by

$$E[Y|Y\geq\alpha] = \frac{Y}{S} \Big|_{Y(X)\geq\alpha} = \frac{\int_X \mathbf{1}_{X|Y(X)\geq\alpha} Y dm}{\int_X \mathbf{1}_{X|Y(X)\geq\alpha} dm}.$$

1.4 Adaptive Diversification: Management of PGR in Ecological Optimum

Let us think about the design of agriculture based on the ecological optimum, using the previously developed theoretical format that uniformly handles the yield and surface of the vegetation distribution with a complex fractal structure. In physiological optimization prevalent in conventional monoculture systems, it was better to eliminate competing vegetation and control the environment to realize the optimal physiological range of cultivated crops. The underlying concern was the cost of material resources necessary for the monoculture optimization in one place.

On the other hand, in ecological optimization, if we interfere too much with the environment, it hinders the elaboration of symbiotic effects that support niche formation (Funabashi 2016a). Instead, it is necessary to search for the spots with favorable environmental and vegetation conditions for target crops, from various ecological situations at each moment. The exploration of a better optimal condition for ecological niche formation that changes dynamically in spatiotemporal patterns becomes an essential management cost in ever-changing open complex systems.

In the absence of prior knowledge, the search cost of the environment that meets the condition can be measured by the amount of selected information in the information theory. Let α^{max} be the maximum yield in an ecologically optimized state of particular vegetation, such as $\alpha^{max} = \max_X(Y(X))$. The area of the niche whose yield range is $[\alpha, \alpha^{max}]$ is calculated using the definition function $\mathbf{1}_X$ across X as

$$\int_{X|Y(X) \in [\alpha, \alpha^{max}]} \mathbf{1}_X dm.$$

Dividing it by per unit area, its occurrence probability $p(\alpha)$ is given by

$$p(\alpha) = \frac{\int_{X|Y(X) \in [\alpha, \alpha^{max}]} \mathbf{1}_X dm}{\int_X \mathbf{1}_X dm}.$$

Usually, each ecological niche is expressed as a unimodal distribution of growth rate on space, and harvesting can be interpreted as taking the sum of random sampling, which means the productivity from a niche is supposed to converge to a normal distribution through the central limit theorem. Based on the normal distribution of yield in each niche, from the property of its cumulative distribution function, we can assume that the lower yield bound α and mean yield $E[Y|Y \geq \alpha]$ form sigmoidal function with respect to the selective information $-\log p(\alpha)$ of $p(\alpha)$. This means that the effective range of minimum and mean yield (which corresponds to the straight section of sigmoid) could be approximated as linear functions of selective information representing the search cost of niche condition.

Taking this assumption further, we construct a simulation of mixed power-law vegetation with multiple species. We define the yield distribution Y_k of niches $k = 1, 2, \dots, k^{max}$ as a series of normal distributions with random weights as follows:

$$Y_k(X) \sim \frac{w_u \sigma_k}{k^{max} \mu_p} N\left(\mu_k, \frac{\sigma_k}{\mu_p}\right),$$

$$w_u \sim U([0, 2]).$$

where $U([0, 2])$ is a uniform distribution on the interval $[0, 2]$ with the mean value 1, and $N(\mu_k, \sigma_k)$ represents normal distribution with the mean μ_k and the standard deviation σ_k that follows Pareto distribution,

$$\sigma_k \sim f(x) = \frac{ab^a}{x^{a+1}}.$$

μ_p is the mean value of the Pareto distribution, and k^{max} is the number of simulated niches (allowing the overlap of not more than k^{max} species), both serve as the regularization factors to satisfy the normalization condition of a probability distribution, $\lim_{k^{max} \rightarrow \infty} \sum_{k=1}^{k^{max}} \int_X Y_k(X) dm = 1$. For simplicity, X was taken on one-dimensional

real value $R: (-\infty, \infty)$, which can be interpreted as a projection from the actual two-dimensional surface to one-dimensional section. A simulated example is depicted in Fig. 1.2. Note that the randomness introduced to $Y_k(X)$ will converge to the normal distribution of occurrence frequency $E[Y_k|Y \geq \alpha]$, by the central limit theorem, which is depicted in Fig. 1.4 (right graphs).

This sampling means to realize a power-law distribution of niche surface on X for a given threshold α , by taking the distribution width and height from a Pareto distribution. Since we do not generally know the yield rate of a species with respect to the niche surface, the yield is multiplied by w_u to introduce a uniform range of variation.

In this article, we only simulate exhaustive global search with a qualitative perspective, which is not concerned by the distribution of μ_k , nor by the chosen value of the parameters and spatial configuration. This means that we are interested in the general form of function that describes the qualitative relationship between the search cost of a niche and its yield. Further quantitative analyses need precise adjustment of parameters from measurement, with an extended model in higher dimensional space according to the number of variables that affect niche condition. Note that the constraint of local search will be affected by μ_k .

Concerning the yield level α , the selective information of k^{max} niches giving yields $Y_k(X)$ more than α is given by $-\sum_{k=1}^{k^{max}} \log p_k(\alpha)$, where

$$\rho_k(\alpha) = \frac{\int_{X|Y_k(X) \in [\alpha, \alpha_k^{max}]} \mathbf{1}_X dm}{\int_X \mathbf{1}_X dm}.$$

We calculated the yield per surface $E[Y_k|Y_k \geq \alpha]$ and regularized minimum yield α_k^{reg} defined as follows:

$$\alpha_k^{reg} = \begin{cases} \frac{\alpha}{\alpha_k^{max}} & \text{if } \alpha \leq \alpha_k^{max} \\ \text{NA} & \text{else} \end{cases},$$

where $\alpha_k^{max} = \max_X(Y_k(X))$ and NA signify not assigned. α_k^{reg} represents the ratio between the minimum harvest line and maximum potential yield, which means the degree of preservation or the inverse degree of exploitation of each niche. If α_k^{reg} is close to 0, the whole niche will be harvested, while completely preserved at $\alpha_k^{reg} = 1$.

We numerically investigated the qualitative relation between the selective information versus yield per surface and regularized minimum yield, with respect to the yield level α . The results are shown in Fig. 1.3. As examined with a single niche, multiple species power-law configuration also accepts linear fitting between search cost and yield. This consistency is due to the diversity introduced with random variables in the model, which would become less plausible in case of small and biased sampling. This numerical relationship leads to a hypothesis that in managing harvest over power-law vegetation structure with sufficiently high species diversity, the search cost could be linearly scalable with respect to the profit from yield.

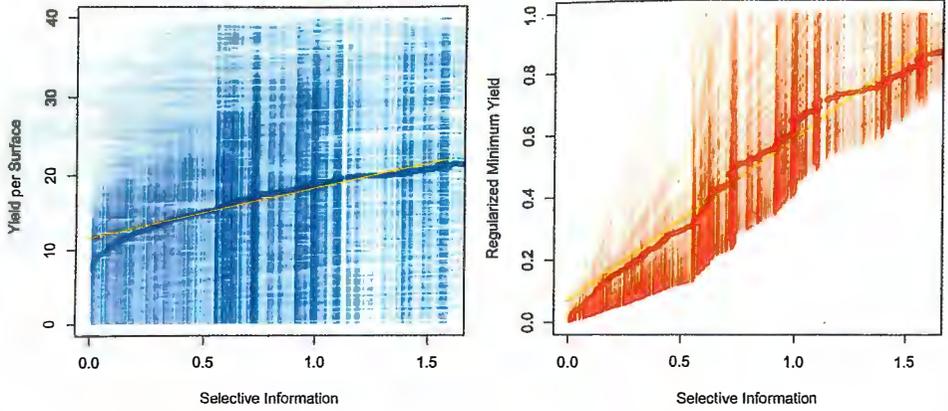


Fig. 1.3 Qualitative relation between selective information of niche $-\sum_{k=1}^{k^{max}} \log p_k(\alpha)$ versus minimum and mean yield. **Left** Selective information versus Yield per surface. Blue dots are the yield per surface $E[Y_k | Y_k \geq \alpha]$, and blue circles are the mean value over all k^{max} niches for each α . **Right** Selective information versus Regularized minimum yield. Red dots are the regularized minimum yield a_k^{reg} , and red circles are the mean value over all k^{max} niches for each α . Orange lines in both figures are the linear regression in the range $[0, 1.6]$ of the horizontal axis before the saturation of simulated yield, which qualitatively defines the efficiency bound of search energy cost. Parameters: $a = 2$ and $b = 0.5$, which results in $\mu_p = 1$ ($\mu_p = \frac{ab}{a-1}$ in case of $a > 1$). Yield level α was divided into 1000 steps from 0 to $\max_k(Y_k(X))$. In total, $k^{max} = 1000$ niches were simulated.

From the viewpoint of a search model, the numerical result conforms to a theoretical assumption that the energy required for search E_s can be defined as the inverse of occurrence probability $\prod_{k=1}^{k^{max}} p_k(\alpha)$, with scale merit s and coefficient c , such as

$$E_s = c \left(\prod_{k=1}^{k^{max}} p_k(\alpha) \right)^{-s},$$

which qualitatively coincides with linear fitting in Fig. 1.3 (orange lines) in logarithmic scale,

$$\log E_s = \log c - s \sum_{k=1}^{k^{max}} \log p_k(\alpha).$$

This means that if the logarithmic increase of search energy remained less than the direct proportion of the yield increase, the management of harvest from power-law distribution of ecological niches is scalable in terms of cost-benefit ratio. The exact profitability could be defined depending on the actual conversion rate between search energy cost and yield profit, scale merit s , and initial cost c .

Let us think in more details for a concrete management strategy. The occurrence probability $p_k(\alpha)$ is given by the exponential function of selective information

$-\log p_k(\alpha)$. As the amount of selective information increases, the probability of such an environment appearing decreases exponentially. The appearance probability of the environment is an exponential distribution with respect to the selective information. This means that the place of the environmental condition that is convenient for the cultivation of the target crops is going to be rare as the demand of minimum yield level α becomes higher. Favorable environments are not necessarily abundant, so finding a suitable environment for a crop will require search cost. However, if we can find and use an ideal environment, we can get a higher yield than cultivating in most other places.

If we can formulate the search method for rare favorable conditions, we can significantly increase the yield in harvesting from ecological optimum. Even if a large yield cannot be obtained at the experimental stage where the search condition is not well understood, it is possible to develop a method of shifting the practical environment to favorable conditions, or introduce crop species that are more adaptive to the current environment, then the average yield can be greatly increased. Actually, among useful plants of wild vegetables and native species, some varieties occupy a wide range of ecological niches in the natural state. If those can be utilized, it is possible to raise agricultural production with little cultivation cost. This strategy is also compatible with the introduction of neglected and underutilized species (Jaenicke et al. 2009).

The fact that the probability of occurrence forms a power-law distribution implies that the mean value of yield in ecological optimum is not practically meaningful. The mean value has significance when the yield is distributed symmetrically and occurs most frequently around the mean value as in the normal distribution. In the power-law distribution, the mean value is not the most frequent occurrence. If we increase the number of samples, at the moment when a rare event occurs, it may change to a drastically higher value than the mean value so far. This fluctuation becomes more apparent when dealing with a small sample in a practical situation. To make it a concrete and practical indicator, the fluctuation is too large with the mean value, since the mean value can potentially diverge to infinity as a mathematical definition of the power law.

It must be remembered that the evaluation of the yield centered on the mean value is a concept based on the conventional farming method presuming artificial control to the physiological optimum state of monoculture. In ecological optimization, the cultivation niches diversify, and they follow a complicated fractal structure and power-law distribution with colossal fluctuation. Indeed, such habitat heterogeneity is a key factor in community processes in the reconstruction of ecosystems (Larkin et al. 2016). Self-sustaining ecosystems require appropriate heterogeneity as an outcome of self-organization over molecular to landscape levels. It is impossible to manage the structure and dynamics inherent in that diversity with only the mean value.

Then, when considering the cultivation method in ecological optimization, what is the index that corresponds to the yield average of the conventional farming method? It should be contextualized in the process of **adaptive diversification** that augments symbiosis among suitable crops using complex niche structures. Rather than targeting

a specific crop and asking how much the single yield in that environment will be, we need to shift the focus to a vegetation strategy at the plant community level and secures the lower bound of total yield, by exploring and utilizing various crops suitable for the given environmental conditions in many ways. In the power-law distribution, the mean value of the whole greatly fluctuates, but it is statistically easier to guarantee the lower bound based on the expectation value of frequently occurring small events. In this sense, the convergent average of the regularized minimum yield α_k^{reg} in Fig. 1.3 is more practically important and reliable in actual management than the yield per surface $E[Y_k | Y_k \geq \alpha]$; the latter mean is only convergent in simulation [with large samples on Pareto distribution with finite mean value ($a > 1$)]. The regularization in α_k^{reg} suppresses the effect of rare big events of α_k^{max} ($\alpha_k^{\text{max}} \gg \alpha$) to zero and weighs more on highly frequent small yield above α ($\alpha_k^{\text{max}} > \alpha$) in an inversely proportional relationship. Such numerical behavior is supported by the mathematical property of power-law distribution, where the harmonic mean converges to a finite value even in case the arithmetic mean diverges to infinity.⁴ By taking the minimum level of yield as a measure of reliable productivity, it reflects the property of harmonic mean as the average of rates between harvest and cost: The harmonic mean of the benefit-cost ratios of unit harvest represents the mean benefit-cost ratio of the total unit productivity, which converges to a finite value with heavier weight on frequently occurring small niches than rare big ones.

Generally, the environment that can be dominated by a single species is rare, and there are many more chances of realization for mixed communities with diverse small niches structure. If we try to introduce over-yielding as symbiotic gain, it is easier to mix small niches to better exploit the statistical nature of ecological optimum (Funabashi 2016a). This strategy supports the compatibility between the self-organization process in natural vegetation and the mixed formation of small niches through the artificial introduction of seeds and seedlings in synecoculture. In contrast, ecological vulnerability and contradiction to multiple ecosystem services are pointed out in conventional methods, which imply that the power-law niche distribution is necessary for ecosystem resilience and represents a functional proxy of adaptive diversification (Funabashi 2017a).

In actual management, even if we cannot predict the high-yielding dominant colony formation of a single crop, the expectation value of yield from small niches in a mixed state of multiple species will stabilize, because the risk of total extinction of community decreases as the number of species increases. As a consequence, the average yield of a specific time and area only comes out as a resulting figure, and it is not directly possible to predict environmental change and future fluctuation of yield based on the average yield.

The overall process of adaptive diversification of crop communities with ecological optimum is schematized in Fig. 1.4. The prediction of future yield from the average at a certain point is a kind of pseudo-correlation that is limited to conventional farming methods, since it posits constant control of the environmental condition under a

⁴Mathematical proof is given in Appendix 3, and a numerical example is simulated in Fig. 1.16 (right).

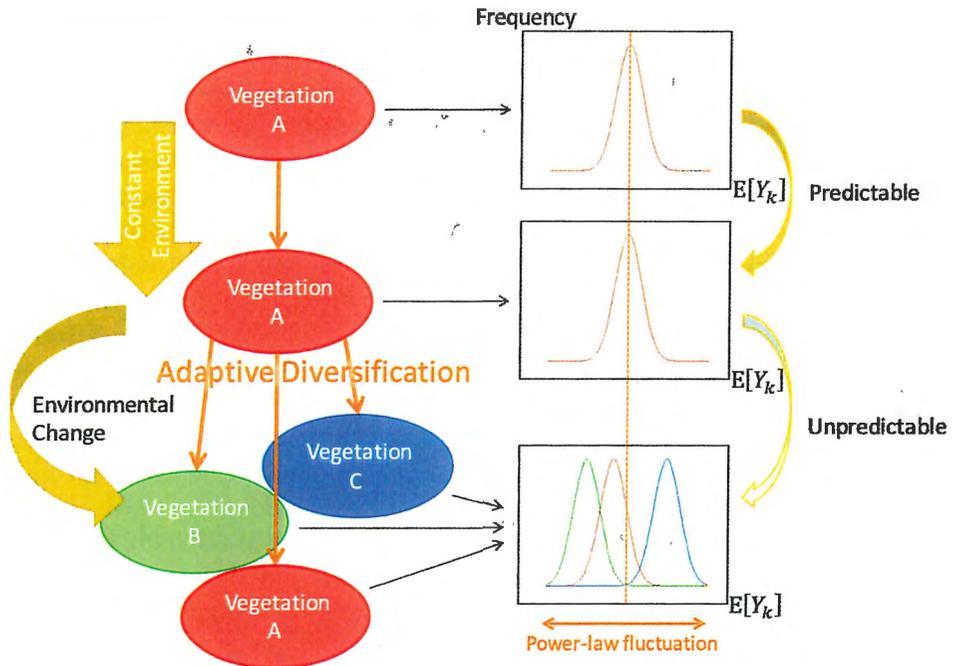


Fig. 1.4 Schematic representation of adaptive diversification of crop communities with respect to environmental fluctuation. The left diagram shows the development of vegetation portfolio from single vegetation A during the constant environment to multiple species A, B, and C to cope with environmental change. The right graphs show the yield $E[Y_k]$ of each vegetation versus its frequency of occurrence, in which red, green, and blue lines correspond to the distribution of vegetation A, B, and C, respectively. The red-dashed line corresponds to the most frequent yield of species A in the past environment, which is difficult to maintain through unpredictable environmental change that induces power-law fluctuation. However, the total yield from all vegetation can be secured by adaptive diversification of niche structure and its consequent productivity

small fluctuation.⁵ If the environment fluctuates, the underlying conditions of niche formation change and then we cannot predict the causal relationship with the yield change unless the response of the vegetation to the environment is wholly known. Ecological niches are continually changing in response to environmental variation. In managing such open complex systems, we need to construct a broad strategy taking into account the diversity of responses to harness latent risks. In order to secure the lower limit of the average yield in a changing environment, it is not sufficient to only discover and rely on successful cases. We also need to consider other strategies in preparation for new contingencies. Adaptive diversification to a wide variation of the scenario by reinforcing the vegetation strategy is necessary; beyond the limitation of the past environment. With this respect, current efforts of transformational adaptation of key crop species to climate change are limited in the diversity of alternative crops and remain in monoculture framework (e.g., Rippke et al. 2016).

⁵Artificially controlled stable monoculture can be described as a dynamical system, as derived in Appendix 1.

The new management strategy based on the self-organized mixed polyculture is similar with the diversified investment for risk hedging in stock trading.⁶ In a changing environment of the market, the unit price at a point in time has only a transient meaning. It is more important to obtain overall comprehensive profits while avoiding risks in long-term changes. With the same idea, in order to ensure a sufficient amount of agricultural production by adaptive diversification, we must take a vegetation portfolio and the field scale that can buffer sufficiently against environmental fluctuations (Funabashi 2016b). Even for crops that one cannot expect much yield at the present stage, we need to invest broadly in considering the possibility of becoming dominant in the future by the transition of niche structure. Besides, it is necessary to design a field with sufficient margin according to the scale of the change. If agricultural land sections decided by humans are not suitable, it will be necessary to revise the scale and topography that can structurally accept adaptive diversification.

Accurate forecasts of productivity based on rigorous measurements are effective only in the short term because environmental changes are known to involve chaotic instability both in climate and ecological dynamics (Cushing et al. 2005). However, plants living with symbiotic effects in a natural ecosystem have been surviving environmental change over more than a billion years and have continued to cover the earth surface repeatedly by constant evolution. In natural plant communities, the power-law distribution is observed in both vegetation-wise and the niche-wise surfaces (Funabashi 2017a). It represents the self-organized state of various niches from dominant to weak species as an outcome of the equilibrium between competition and symbiosis. Consequently, multiple buffering interactions are potentially prepared to cope with environmental changes, in a way that secures a certain amount of biomass by increasing some partial vegetation newly adaptive to the environment. In the land with necessary sunshine and rainfall, the absence of desertification is a manifestation that plants adequately buffer environmental changes due to naturally occurring adaptive diversification. The primary production does not deplete in highly established ecological optimum. It is the matter of replacing natural vegetation with useful plants to apply these dynamics into agricultural production.

It is in principle impossible to keep environmental conditions fixed, in the natural environment where there exist overlaps of multi-scale fluctuations in daily microscale, seasonal mesoscale, and macroscopic climate change. There is no guarantee that crops cultivated in a physiologically optimal range in past decades can grow at the same cost in the future. Recently, it has been reported in various places that the influence of global warming is reshuffling the wildlife (Pecl et al. 2017), which will call for a strategic mobilization of suitable crops in the global scale. Production areas that have relied on a small number of products based on conventional farming must fail at the moment when control cost of the environment exceeds productivity. Especially in terms of soil fertility, rock weathering is reported to amount

⁶Other than stock trading, adaptive diversification is similar to recently prominent e-commerce strategy that is based on power-law distribution. Sales of Internet shopping sites such as Amazon.com is known to follow the power-law distribution, which is also called as “the long tail” (Anderson 2008).

to $\frac{1}{4}$ of total soil nitrogen source worldwide (Houlton et al. 2018), which calls for the importance of the vegetation based on ecological optimum (i.e., natural vegetation and self-organized mixed polyculture such as in synecoculture) to prevent nitrogen runoff and to store more atmospheric nitrogen and carbon locally at each area.

In order to secure food production in the face of population growth, a viewpoint of adaptive diversification with the perspective of open systems management becomes necessary (Funabashi 2016b; 2017c). This approach can be translated to making use of the evolutionary mechanism in which plant communities in the natural state have been thriving and constructed the topsoil (Funabashi 2016a). It is to deliver the benefit from, while reinforcing the functioning of, the most highly elaborate buffer system in the evolutionary history of the Earth System.

1.5 Ecological Recapitulation Theory: Parallelism Between Phylogenetic and Phase Diversities

Ecological interactions at community scale play essential roles in the evolution of the maintenance mechanism of biodiversity (Guimarães et al. 2017) and consequent primary productivity (Funabashi 2016a). Recently, toward the elucidation of the relationship between biodiversity and ecosystem functions, functional diversity that takes into account the intra and interspecific trait variability and phylogenetic diversity that incorporates evolutionary relationship between species is widely investigated (Cadotte et al. 2011; de Bello et al. 2011; Albert et al. 2012; Carmona et al. 2017). The effect of functional diversity and phylogenetic diversity on the aboveground biomass has been verified in field experiments in grasslands (Flynn et al. 2011). Functional and phylogenetic diversities were found to be effective indicators to explain the changes in ecosystem function, which implied the importance of the evolutionary process that created mutations among species traits.

The integrative approach between the evolutionary process and ecological succession is also underway. Long-term increases in the effect of biodiversity on ecosystem functions have been reported in field experiments (Reich et al. 2012). A part of such temporally cumulative effect was revealed as the improvement of ecosystem functions through the promotion of niche division across generations in highly diversified communities (Zuppinger-Dingley et al. 2014).

In order to apply this evidence from community ecology to the food production in ecological optimum, we need to establish a complexity measure for interactive management model taking both phylogenetic and succession phase diversity into account. The complexity measures in the context of open complex systems are defined as a set of low-dimensional proxies that incorporate useful features for the development of the system's diversity and effective management strategy (Funabashi 2017b). In the case of the natural ecosystem, succession stages of soil and land ecosystems are integrated and proposed as a complexity measure for the management of material cycles in ecological optimum (Funabashi 2016c). As an example of food production,

synecological farming adopts the complexity of evolutionary traits of land plants as an index of assessment and control of vegetation, which is also associated with the development of species traits through succession stage (Funabashi 2016b).

The similarity and correspondence of the developed traits between ecological succession and evolution of land plants are useful for the actual management of mixed plant communities, in a way that integrates both functional and phylogenetic diversity. This accordance can be termed as “**ecological recapitulation principles**,” taking after the historical notion of “ontogeny recapitulates phylogeny” in embryological parallelism. The ecological recapitulation principles can be listed as follows, as mutual characteristics of plant species that have been observed to develop both in ecological succession and phylogenetic evolution of plants:

- Growth height (biomass)
- Vascular development and lignification (tree structure, an increase of lignin)
- Complexity and resilience of ecological network based on the diversity of competition and symbiosis, its spatiotemporal scale such as history dependence
- Diversity of secondary metabolites
- Complexity of food chains
- Buffering and retention time of trace elements in soil such as nitrogen, carbon, water, oxygen, mineral, and phosphorus
- Utilization of fauna (e.g., development of fruit pulp and seed strategy) and its spatiotemporal scale (e.g., Synchronization of bird migration and fruiting phenology)
- Water supply capacity of the root system.

These common features can be formalized as “vegetation succession recapitulates evolution,” though not in the sense of a scientifically rigorous description. It is rather for a practical matching between succession stage and phylogenetic diversity to develop an integrated proxy for the management of plant communities.

One of the simplest ways to construct such a measure can be achieved with a geometrical mean between phylogenetic and succession stage diversity.⁷ Figure 1.5 schematically represents an example. The geometrical mean C_g between phylogenetic diversity d_p and succession stage diversity d_s can be formalized as

$$C_g = \sqrt{d_p d_s}.$$

This measure coincides with the adoption of gamma (γ) diversity that describes the total species diversity in target ecosystem, with the considerations on alpha (α) diversity in phylogeny d_p and beta (β) diversity in succession stage d_s (Whittaker 1960).

As an alternative perspective, different vegetation types are reported to correlate with different fractal dimensions in satellite image analyses (Nayak 2008), which

⁷Note that we can find other characteristics of geometrical mean that are compatible with the nature of biodiversity and ecosystems functioning. Another example of application in the context of food security concerning product diversity is developed in Appendix 2.

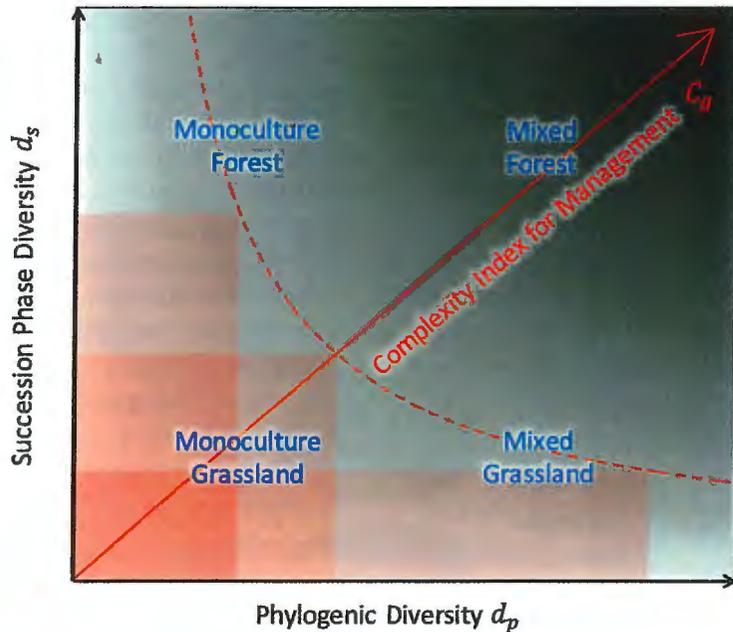


Fig. 1.5 A typical example of complexity measures that integrate phylogenetic and succession phase diversity. The value of geometric mean C_g between d_p and d_s is shown with a grayscale gradient, with a contour line example with a red-dashed line. The surface of red rectangles corresponds to the value of C_g^2 at the upper-right corners, which are conserved along the red-dashed line. Typical vegetation physiognomy of the highest succession stage with different combinations of d_p and d_s is described in blue. The overall complexity of evolutionary traits that support primary production of naturally organizing ecosystem develops qualitatively along the red arrow and grayscale, as an integrated diversity of phylogeny and succession stage

provide another source of complexity measure that should work in a complementary way with the ecological recapitulation principles.

Actual management requires an intensive operation on each scale of species diversity for global optimization of utility (Funabashi 2016a). Beyond existing biodiversity, operational diversity with newly introduced species becomes central when considering food production based on the diversity of plant genetic resources.

1.6 Operational Ecological Diversity and Extended Notions of Biodiversity and Ecosystem Services

There are more than 30,000 edible plant species recorded in the world, out of which we depend only on 30 crops for 90% of calories in our food. While there are 7000 plants used for food, commonly cultivated species in agriculture are limited to 120 (Yong et al. 2006). This highly homogenous situation of crop diversity distribution wipes out natural biodiversity through agricultural land conversion, which is consid-

ered as a principal driver of the sixth massive extinction in life history (Pereira et al. 2010).

To overcome the fundamental trade-off between biodiversity and productivity in conventional agriculture, synecological farming (synecoculture) sets a series of inclusive strategies to intensively augment species diversity in the farming plot and surrounding ecosystems (Funabashi 2016a, b, 2017a). Such human-driven introduction of new species for multiple socio-ecological purposes and total enhancement of biodiversity and ecosystem functions stems from the conception of operational ecological diversity (Fig. 1.6), which extends the notion of biodiversity and ecosystem services beyond the context of conventional agriculture and ecology (Fig. 1.7).

Operational ecological diversity in Fig. 1.6 includes all sorts of human activity possible in relation to biodiversity, except transgenic technologies for the risk con-

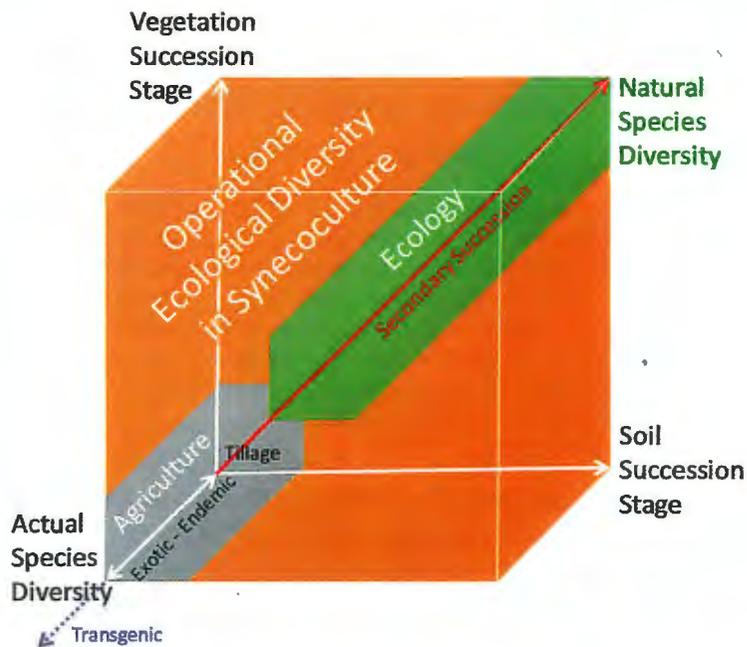


Fig. 1.6 Operational ecological diversity with respect to species diversity, succession stages vegetation (aboveground), and soil (underground). Tillage-based agriculture only treats crop species diversity without elaborate soil ecosystem that can only be formed through long-term vegetation succession (gray area). The formation of soil structure that develops over the years to decades in ecological optimum critically lacks even in advanced conservation of agriculture practices, thus remaining at the stage of reduced tillage and fertilization. On the other hand, studies in ecology mainly treat secondary succession of natural vegetation (red arrow) over a long period, with more importance on endemic species and natural species diversity for the conservation value (green area). In contrast, operational ecological diversity in synecoculture can explore all combinations of endemic and exotic species through intensive introduction in various soil and vegetation succession stages in three-dimensional space (orange volume). Under the concern of interspecies gene transfer problem, transgenic technologies are refrained from the concept of operational ecological diversity in synecoculture

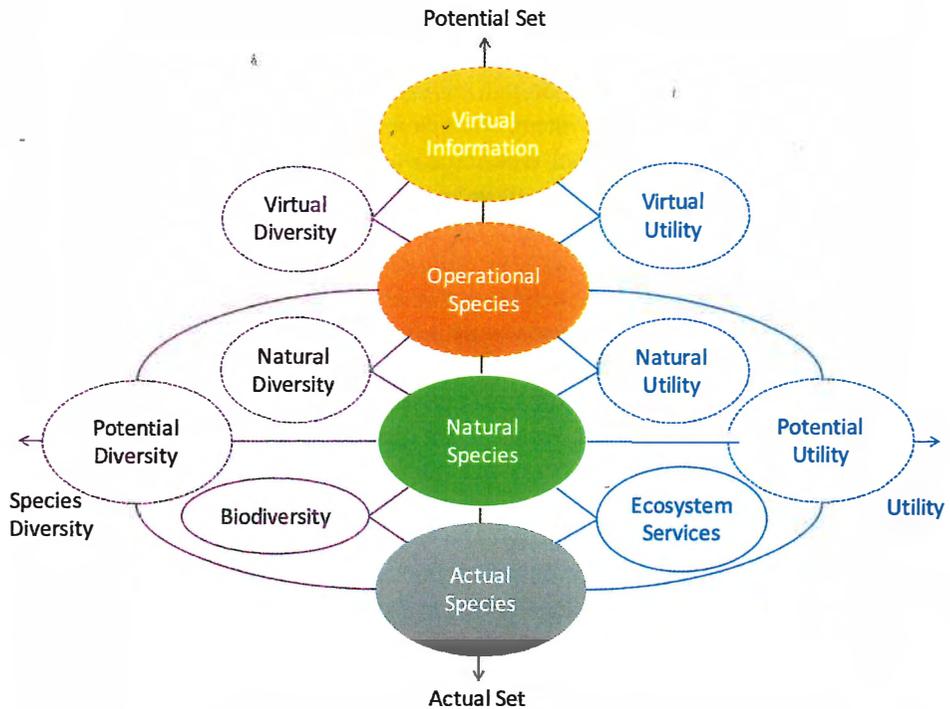


Fig. 1.7 Extended notion of biodiversity and utility in synecoculture. Usually, the loss and recovery of biodiversity are discussed in a comparison between naturally occurring maximum species diversity (green circle) and actually observed species diversity (gray circle), on which various utilities including economic benefit are termed as ecosystem services. With operational species diversity (orange circle) and virtual information of other ecosystems (yellow circle), we can think of the extension of these concepts (dashed circles) as listed in Sect. 1.6. Colors of circles conform to those of divided area in Fig. 1.6

cerned on the interspecies gene transfer. Since conventional agriculture produces under the constraint of physiological optimization, it ignores most of the ecological succession. On the other hand, ecological studies focus on the natural succession of vegetation under varying degrees of genetic and ecological disturbance, but a wide range of introducible species remains out of concern. Current food industry and academic disciplines only occupy a limited area compared to all possible ecosystems realizable by human assistance.

By considering the possibilities of operational ecological diversity, it is possible to extend the concept of biodiversity and ecosystem services as schematized in Fig. 1.7. Here, we take neutral terms as “species diversity” and its “utility” to deconstruct and expand the concepts. Newly derived concepts (dashed circles in Fig. 1.7) concerning the anthropogenic augmentation of ecosystems are as follows:

- Operational species: It describes a set of possibly introducible species, whether wild plants or crops, in a given environment by human assistance. The introduc-

tion should be based on the open-field environment under coexistence of various ecological niches.

- **Virtual information:** It represents digitalized information on biodiversity and other related information to the ecosystem, such as meteorological data, in all parts of the world. It includes the global databases of biodiversity (e.g., GLoBI 2017) and recorded traditional knowledge of indigenous peoples and local communities (DGM 2017). It is a potential resource, e.g., for future climate change adaptation, which could be reflected in the set of operational species in the future.
- **Natural diversity/utility:** Taking a reference to the set of operational species, what is realized in natural state ecosystem is only a subset of what is possible in social–ecological interaction in, e.g., preservation state. Therefore, the species diversity realized by natural process is termed as “natural diversity” to describe the species diversity that nature has chosen from the set of operational species and its utility as “natural utility.” As natural ecosystems have only limited and partial economic profit for industrial activity, it only reflects a part of possible realization under natural selection.
- **Potential diversity/utility:** By comparing the sets of “operational species” and “actual species,” one can estimate the true potential of biodiversity and its utility realizable with plant communities managed by humans in ecological optimum.
- **Virtual diversity/utility⁸:** Information and Communication Technologies (ICT) can store, search, and share various kinds of information relevant to biodiversity and its management, which will serve for the comprehensive exploration of “operational species” set and potential utilities for future adaptation to changing environment, which can be described as “virtual diversity” and “virtual utility,” respectively. It is important to consider the use of virtual diversity to provide essential supports for the exploration of non-monetary benefit-sharing, such as open databases and research uses.

These concepts provide a basic framework in designing concrete strategies of the adaptive diversification theoretically explored in Sect. 1.4, such as the implementation of vegetation portfolio in synecoculture.

1.7 Experimenting Anthropogenic Megadiversity

We have experimented an extreme case of adaptive diversification with a small-scale synecoculture farm in Tokyo, Japan. During April 2011–March 2017, we have intro-

⁸Virtual diversity does not exist in real ecosystems but only in human-prepared databases, which serves as the reservoir of resilience in the future adaptation of ecosystems. In stable ecosystems with saturated species diversity, virtual diversity does not make any significant contribution to ecosystem functions, just like redundant species in the redundancy hypothesis. It can, however, be a source of compensation for the loss of ecosystem functions under the rivet hypothesis in dynamical change and important accelerator of ecological transition. In either case, the virtual utility can contribute to enhancing ecosystem services for human purposes, such as the adaptation of the product portfolio to market value.

duced commercially available 379 varieties of crops from 81 families that comprise more than 1000 cultivars, as listed in Table 1.1. Spatial configuration was chosen randomly following the general principle of management in synecoculture (Funabashi 2016b). The field view is shown in Fig. 1.8. This experiment aimed to realize anthropogenic megadiversity as an augmented ecosystem with respect to biodiversity and self-organized ecosystem functions (Funabashi 2016a), through the intensive introduction of operational species diversity and utility defined in Sect. 1.6 (Fig. 1.7).

In consistency with Fig. 1.6, ecological diversity realized with synecoculture extended beyond conventional agriculture practice and field experiments in ecology: In terms of vegetation succession, secondary succession from bare land during six years with introduced and naturally occurring species was observed, which deviates from the culture environment under the control method of conventional farming (such as tillage, fertilizer, and chemicals), also involving much wider varieties of exotic crop species than natural succession.

In terms of the succession of the soil ecosystem, short-term species control experiment was performed to elucidate the relationship between management strategies of synecoculture and self-organized ecosystem functions (Funabashi 2017a). Water retention and permeability were found to correlate with the aboveground development of vegetation following ecological optimum. Soil microbial diversity and activity were also found to correlate with the operational species diversity, attaining highest grade of the production and regulating services compared to other reported examples of farmland.

These ecological successions have led to the phase transition of acceptable crop species in no-tillage and no-fertilizer conditions, as well as sufficient regulation of pest through self-organized food chain under no-chemical condition.

We also investigated the relationship between operational species diversity for different surface scales, based on the experiment data in (Funabashi 2017a). The results are summarized in Fig. 1.9: Fig. 1.9a shows the diversity of species and its taxonomical family with respect to the measuring surface generated by the $n = \{1, 2, 4, 8, 16, 32\}$ tuples from 36 spot measurements. At the smallest scale ($n = 1$), it corresponds to the α -diversity of observation spots, which are merged to the γ -diversity of the whole plot at the largest limit ($n = 36$). The species–area relationship shows typical power-law relation observed in the natural ecosystem (Arrhenius 1921), with slight saturation toward the whole plot scale, possibly due to the spatial constraint of the experiment. Plant species diversity ranges between 10 and 70 species, which fits well with the most probable niche diversity distribution by $\%$ -measurable sampling from various power-law vegetation, as simulated in Fig. 1.1. Notably, the diversity of herbaceous species in Fig. 1.9c ranges over 10–50+ species, which coincides with the small sampling case $N = M = 100$ in Fig. 1.1. It implies that the measurement covers sufficiently appropriate spatial scales for the actual power-law gradient parameter a .

The variance of species and family diversity in Fig. 1.9b, d corresponds to the measures of β -diversity within the plot. In Fig. 1.9b, interspecies diversity increases as the scale of measurement expands (except the combinatorial saturation as it approaches the whole plot scale at $n > 18$). Therefore, the functional diversity that is supported

Table 1.1 List of 81 taxonomical families comprising 379 varieties introduced in 250 m² at Todoroki synecoculture farm in Tokyo during April 2011–March 2017

Family	#Varieties	Cannabaceae	1	Juglandaceae	2	Polygonaceae	5
Actinidiaceae	1	Caprifoliaceae	9	Lamiaceae	45	Primulaceae	2
Adoxaceae	2	Caryophyllaceae	4	Lardizabalaceae	2	Ranunculaceae	1
Aizoaceae	1	Chenopodiaceae	1	Lauraceae	2	Rosaceae	28
Alismataceae	1	Commelinaceae	1	Malvaceae	7	Rubiaceae	2
Alliaceae	9	Convolvulaceae	4	Meliaceae	1	Ruscaceae	1
Amaranthaceae	4	Cornaceae	1	Moraceae	2	Rutaceae	7
Amaryllidaceae	4	Crassulaceae	1	Myricaceae	1	Sapindaceae	1
Apiaceae	13	Cucurbitaceae	10	Myrtaceae	9	Saururaceae	1
Apocynaceae	2	Cupressaceae	1	Oleaceae	1	Scrophulariaceae	1
Araceae	1	Dioscoreaceae	1	Onagraceae	2	Solanaceae	8
Araliaceae	5	Dipsacaceae	3	Orchidaceae	1	Theaceae	2
Asparagaceae	1	Elaeagnaceae	2	Oxalidaceae	1	Urticaceae	1
Asphodelaceae	3	Equisetaceae	1	Papaveraceae	1	Valerianaceae	3
Asteraceae	42	Ericaceae	3	Passifloraceae	1	Verbenaceae	3
Basellaceae	2	Euphorbiaceae	1	Pedaliaceae	1	Violaceae	1
Berberidaceae	1	Fabaceae	17	Phytolaccaceae	1	Vitaceae	2
Betulaceae	3	Fagaceae	2	Plantaginaceae	4	Xanthorrhoeaceae	1
Boraginaceae	3	Geraniaceae	4	Poaceae	15	Zingiberaceae	3
Brassicaceae	36	Hypericaceae	1	Podocarpaceae	2	#Total	#Total
Campanulaceae	1	Iridaceae	1	Polemoniaceae	1	81	379



Fig. 1.8 View of Todoroki synecoculture farm in Tokyo, Japan, that introduced 379 varieties (more than 1000 commercial cultivars) in 250 m² during six years as listed in Table 1.1. Picture taken on May 21, 2016

by interspecies variability may enhance ecosystem functions within this scale. On the other hand, taxonomical diversity at the family level shows consistency or slight decrease with respect to scale change in Fig. 1.9b. It may imply the stability of ecosystem functions that are supported by phylogenetic diversity. Such inferred difference of functional contribution between interspecies and phylogenetic diversity may arise from the characteristics of the operational species diversity introduction specific to this experiment.

Figure 1.9c shows the breakdown of species diversity between herbaceous and arboreal plants, introduced and naturally occurring or spontaneous species, and edible and non-edible species (see Funabashi 2017a, for definition). In terms of power-law niche formation, it is the introduced and/or edible species that are contributing to such formation, more than spontaneous and/or non-edible species that remain in the exponential distribution (differences shown with red and blue arrows, respectively, in Fig. 1.9c).

As shown in Fig. 1.9d, the contribution to β -diversity also shows a similar difference between introduced/edible and spontaneous/non-edible species. The β -diversity within the plot was principally augmented by the introduced and/or edible species (except the combinatorial saturation as it approached the whole plot scale at $n > 18$), compared to the spontaneous and/or non-edible species that did not show an increase by scale.

The overall results imply that even with limited small areas, the human-driven introduction of operational edible species diversity with synecoculture strategies is able to establish the species–area relationship that follows qualitatively similar distribution as a natural ecosystem. The whole process can be formalized as a replication of ecological optimum by replacing secondary succession with introduced species. As the operational species set contains larger areas of diversity and utility than nat-

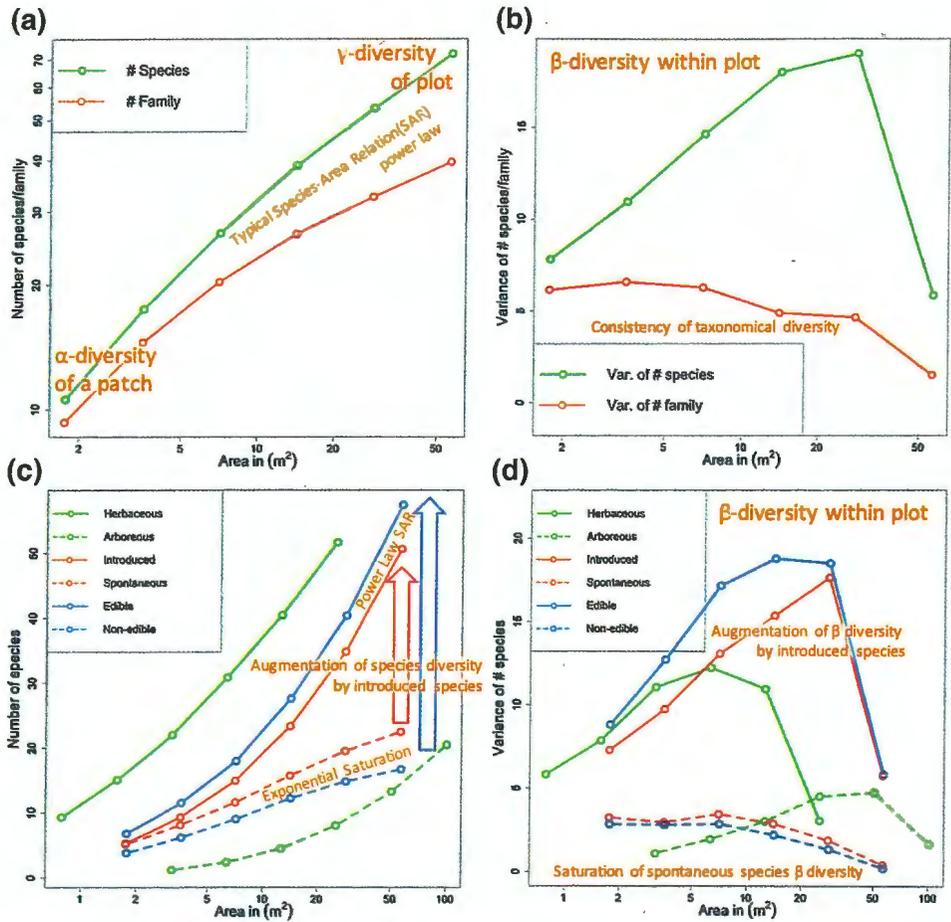


Fig. 1.9 Relationship between species diversity and surface in Todoroki synecoculture farm in June 2015. For experimental design and measurement methods, see Funabashi (2017a). In **a**, **b**, **c**, and **d**, based on the smallest sampling area for herbaceous species (circle with 0.5 m radius) and arboreous species (circle with 1 m radius), species and family diversity was counted on average surface (circle with 0.75 m radius), and higher surface scales were randomly generated by combining $n = \{2, 4, 8, 16, 32\}$ sets from 36 sampling spots. The variance was calculated from 1000 random numerical sampling for each surface scale. **a** Sampling area versus the number of plant species (green) and taxonomical family (red) in double logarithmic scale. **b** Sampling area in logarithmic scale versus variance of plant species diversity (green) and taxonomical family diversity (red) in linear-log scale. **c** Sampling area in logarithmic scale versus number of herbaceous species (green solid line), arboreous species (green-dashed line), introduced plant species (red solid line), naturally occurring plant species (red-dashed line), and edible species that were utilized in synecoculture (blue solid line) and non-edible species that were not yet utilized in synecoculture (blue-dashed line). **d** Sampling area in logarithmic scale versus variance of the number of herbaceous species (green solid line), arboreous species (green-dashed line), introduced plant species (red solid line), naturally occurring plant species (red-dashed line), and edible species that were utilized in synecoculture (blue solid line) and non-edible species that were not yet utilized in synecoculture (blue-dashed line). See Sect. 1.7 for the explanation of the texts in orange

ural ones in Fig. 1.7, there is a possibility of increasing biodiversity and associated ecosystem functions with synecoculture, beyond natural preservation state.

In the context of the argument between single large or several small reserves of equal area (SLOSS) (Laurance 2009), it may be effective to allocate synecoculture in a fragile small area such as forest edge. As species with narrow distribution areas are generally harder to be included in protected areas, local extinction is likely to occur for those species without strategic inclusion (Akasaka et al. 2017), and synecoculture can provide a modality to integrate such long-tail conservation efforts and local economic activities.⁹ Globally, it is of future expectation whether the anthropogenic introduction of operational species diversity could accelerate both evolutionary adaptation and evasion from extinction in endangered zones, such as overly disturbed tropical rainforest by forest fragmentation (Laurance et al. 2004). This perspective involves the alteration of ecosystem with newly introduced species, which should take into consideration the trade-off between development and conservation in the context of population growth, legal preparation on access and benefit-sharing of plant genetic resources (CBD 2010a; Paroda et al. 2017), and consider how to design sustainable social-ecological system as an alternative stable state other than the global collapse of biodiversity (Barnosky et al. 2012).

1.8 Virtual Diversity that Supports the Extension of PGR

In order to assess operational diversity comprehensively, one needs supportive virtual information as wide as possible to explore the possibility of operational species set (Fig. 1.7). Such relevant ecological information can be obtained from global and commercial databases and other field experiments.

Figure 1.10 shows a part of virtual information from field experiments in Japan that supported the megadiversity experiment of Todoroki synecoculture farm in Sect. 1.7. In order to attain the maximally possible operational diversity, virtual information should be elaborated ahead of the future ecological succession and environmental change. Not only the possibility of species diversity but the management knowledge should also be shared as virtual information, which helps knowledge transfer in citizen science practice (Funabashi 2013).

Such a strategy of information investment becomes particularly crucial in zones sensitive to climate change and experiencing ecological regime shift such as desertification. From synecoculture experiment in Burkina Faso, it has been reported that it is possible to reverse the regime shift from bare desert to mixed forest formation, with all types of species that can be found in mature forest, covering a wide range of the complexity measure in Sect. 1.5 (Tindano and Funabashi 2016; Funabashi 2017a). The field proof conforms to the theory developed in Sect. 1.4 that reproduces and makes use of the Earth System's buffering function through adaptive diversification of plant community with operational species diversity. As a drastic transition between

⁹More theoretical details in Appendix 3.

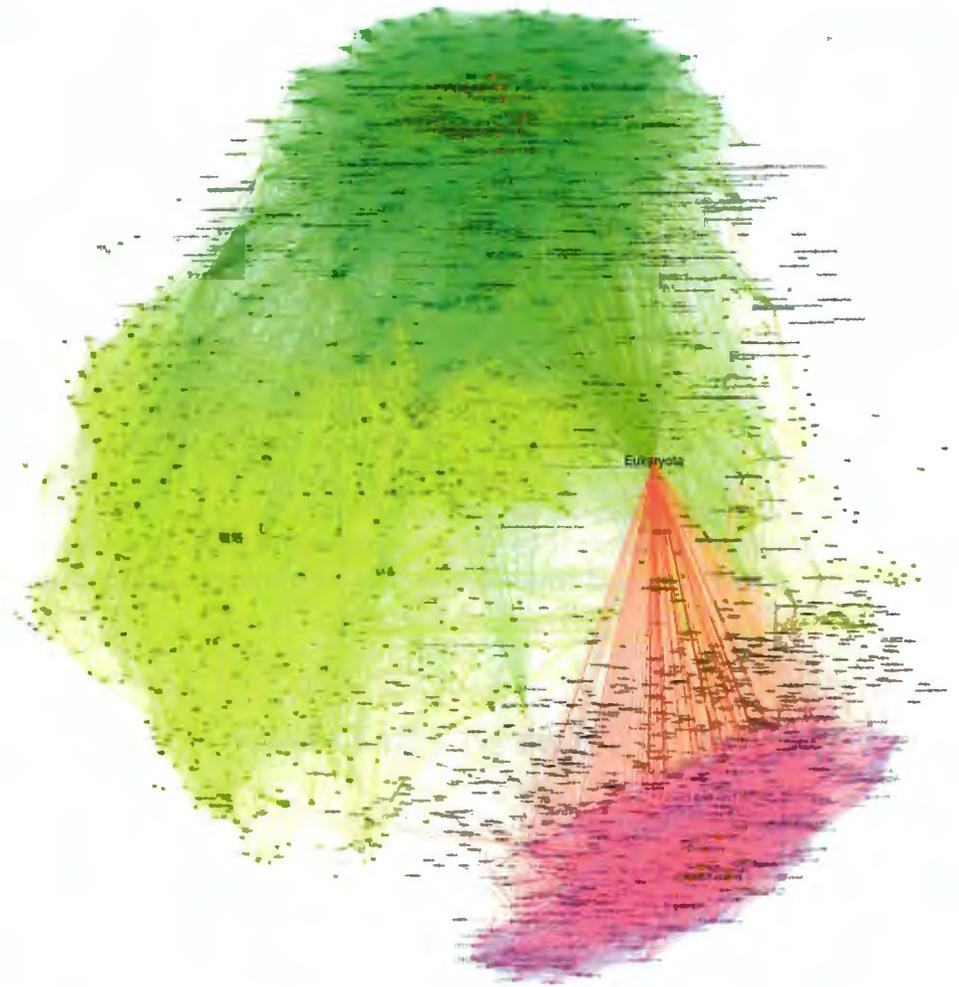


Fig. 1.10 Graph visualization of the virtual information for the management of operational species diversity in Todoroki synecoculture farm. Based on ten experimental plots of synecoculture in Japan during April 2011–March 2012, possibly introducible or naturally occurring 1130 plant and insect species and related knowledge are depicted as a graph based on the association of observation. Green nodes correspond to the cluster of virtual plant species diversity, magenta that of insect species, and yellow that of morpheme (nouns, verbs, and adjectives) extracted from the management knowledge written as Japanese texts. The morphological analysis of Japanese texts was performed using RMeCab library (version 0.996) on R (MeCab 2017). Graph visualization with Gephi (Bastian et al. 2009)

different ecological states occurs in a short period, potential diversity and utility also change to a totally different capacity; therefore, the virtual information that incorporates a future extension of operational diversity becomes crucially important for the sustainable management.

Figure 1.11 shows an example of virtual information in relation to actual species diversity in the experiment. For real-time processing and use of ecological big data such as with the combination of actual environmental and virtual information, computing technologies such as machine learning and artificial intelligence will be required to scale up the management (Funabashi 2017c; Funabashi et al. 2017). This information can be efficiently and interactively treated with emerging human—computer interfaces such as augmented reality (AR) as represented in Fig. 1.12.

With the scenario of adaptive diversification of plant genetic resources, the Information and Communication Technologies (ICT) will become an essential infrastructure for the achievement of global sustainability goal such as Aichi biodiversity targets (CBD 2010b) and UN Sustainable Development Goals (UN 2015), together with the institutional need of developing access and benefit-sharing clearing-house for the equitable implementation of operational species diversity (CBD 2010a, 2017).

1.9 Adaptive Diversification Experiments in International Level

Climate change is triggering worldwide geographical redistribution of plant and animal species (Pecl et al. 2017). Conservation activities beyond national jurisdiction are essential for the sustainable use of biodiversity at large scale (UNEP 2017). Adaptive diversification across national boundaries will increase its importance to secure biodiversity and food production.¹⁰ Under this perspective, we extended the operational diversity toward the international exchange of plant genetic resources (PGR) between synecoculture experimental farms in Japan, Taiwan, and Burkina Faso.

The number of exchanged commercial varieties is shown in Fig. 1.13. Since Japan is situated in a temperate zone, Burkina Faso in semi-arid tropics and Taiwan between temperate and tropical zones, main overlaps of introducible species can be found between Japan–Taiwan and Taiwan–Burkina Faso. Especially, Taiwan can serve as an integrated validation site in both temperate and tropical conditions, as most of the species are overlapped with the other countries. As soil humidity can be controlled by irrigation and density of vegetation, and the sunlight is consistently available in open-field culture, the temperature is the limiting factor among other environmental parameters. The geographical distributions of these countries can encompass a wide range of operational species diversity introducible to similar climate condition, which serves as a screening for the introduction to megadiverse countries such as

¹⁰A simple simulation on food security grounded on product diversity is shown in Appendix 2.

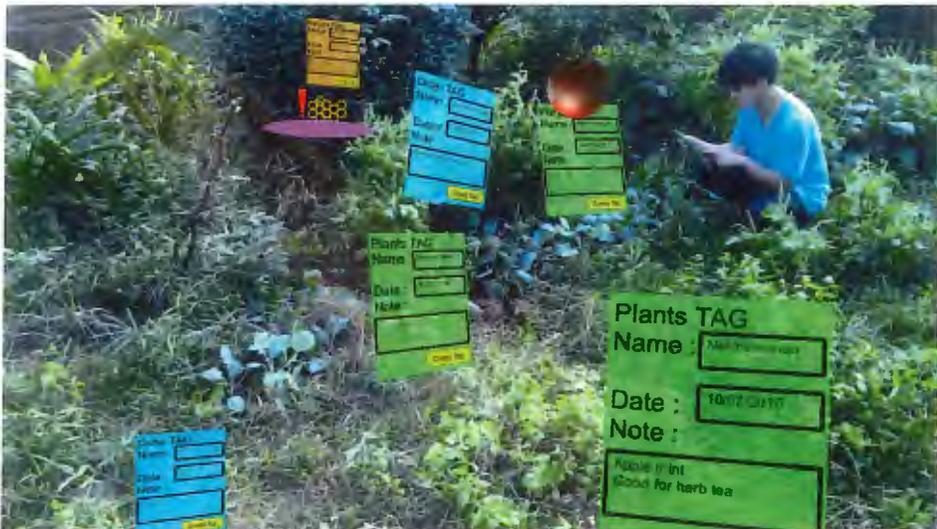
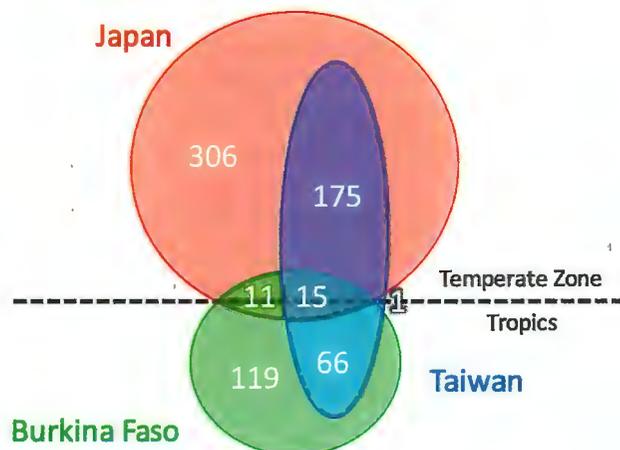


Fig. 1.12 Example of the management interface using augmented reality (AR) technology. Through portable and wearable devices with a camera such as a smartphone, tablet computer, and glass interface, one can view and manage virtual information related to actual vegetation on-site, using this information overlapped with the real world in a non-invasive way to the environment

Fig. 1.13 Venn diagram on the number of commercial crop varieties exchanged between synecoculture experimental fields in Japan (red), Taiwan (blue), and Burkina Faso (green). The dashed line shows the separation between the temperate zone (above) and tropics (below)



India (Funabashi 2017a) and small tropical countries vulnerable to climate change (Petherick 2012).

The choice of exchanged varieties at this stage depends only on heuristics based on commercial availability and not yet exhaustive in terms of potential operational diversity. The exchange was conducted with solely dry commercial seed package, following the direction of local authorities such as quarantine and with consideration to the international agreement such as the Cartagena Protocol on Biosafety (CBD 2000) and the Nagoya Protocol on access and benefit-sharing (CBD 2010a).

Considerations on population and ecological genetics of native and introduced flora were also taken into account (Richards et al. 2016). Locally restricted varieties such as those of *glycine max* in Taiwan were refrained from export. The experiment in Burkina Faso followed the FAO guideline for mainstreaming biodiversity (FAO 2016; Tindano and Funabashi 2017) and respected access and benefit-sharing (ABS) guideline in African Union (UA 2015).

Exhaustive realization in diversity and quantity of operational plant genetic resources should wait for the preparation of national ABS laws with proper Prior Informed Consent (PIC) and Mutually Agreed Terms (MAT) formats, which are still absent in many countries including Japan, Taiwan, and Burkina Faso.

At the current stage, the international exchange of PGR in synecoculture is limited in a small quantity of commercially available and commonly cultivable species. Traditional knowledge on these PGR was occasionally shared under the open-source principle based on the provider's will. In order to maximize the resilience and adaptation capacity to climate change, it is urgent to establish consistency between ABS-PIC/MAT, quarantine systems, and monetary/non-monetary benefit distribution for the large-scale implementation of adaptive diversification at international level.

1.10 Conclusion

We theoretically examined the power-law distribution of ecological niches in plant communities and developed a global strategy of adaptive diversification and complexity measure reflecting functional diversity for the management of food production in ecological optimum. We extended the notion of biodiversity and ecosystem services with operational and virtual ecological diversities and reported the synecoculture experiments constructed on this framework. Future development of ABS legislation compatible with the anthropogenic augmentation of ecosystems is required to maximize the resilience to climate change and compensate for the biodiversity loss with the operational ecological diversity.

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Appendix 1: Construction of Lebesgue Integral in an Ecosystem Data Set

This section summarizes the basics of Lebesgue integral, which gives the mathematical basis of analysis in ecosystem data with power-law configuration. The integration of the probability measure can be implemented by a search algorithm, and an IT platform such as content management system (CMS) is required for the analysis of massive data (Funabashi 2017b).

Lebesgue Integral as Probability Integral Over Real Number and Integration of the Probability Measure on a Set

In order to give the calculation of the probability by Lebesgue integral on the real parameter space, consider Lebesgue measurable space (X, \mathcal{B}, μ) .

The normalization condition by the Riemann integral of the probability density function $p(x)$ on $X = \mathbf{R}:(-\infty, \infty)$, $x \in X$ is given by

$$\int_{-\infty}^{\infty} p(x)dx = 1.$$

The Riemann integral is defined by the limit value of infinite series. Therefore, fractal figure, etc., which involves the limit operation in the definition of the function $p(x)$ itself, will encounter double limit operations, and the analysis becomes extremely difficult. Since vegetation pattern has the property of fractal figure, the calculation of analytical solution is difficult when extrapolating measurement value to fractal figure model.

In such a case, it can be calculated using the Lebesgue integral. Let μ be the Lebesgue measure on \mathbf{R} , then the normalization condition of probability by Lebesgue integral is

$$\int_{\mathbf{R}} p(x)d\mu = 1.$$

Then, the Lebesgue integral of the probability satisfying $p(x) \geq \alpha$ is given by

$$\int_{X|_{p(x) \geq \alpha}} p(x)d\mu.$$

This can be calculated for the distribution of $p(x)$ with a complex configuration, such as fractal distribution on \mathbf{R} , by the Lebesgue convergence theorem. Intuitively, since the phase structure of the completely additive class \mathcal{B} is defined, the convergence of the infinite sequence can be treated in a topologically simple manner, by putting

the limit operation that defines the fractal function outside of the integration. The probability density function $p(x)$ on $X = \mathbf{R}^n: (-\infty, \infty)^n$ is also given in the same way.

In order to calculate the probability on a symbolic set S , not on \mathbf{R}^n , it is necessary to determine the completely additive class \mathbf{E} on S and the probability measure P . In the measurable space (S, \mathbf{E}, P) , let 1_S be the definition function of S , then the normalization condition of the probability measure is

$$\int_S 1_S dP = 1.$$

The occurrence probability that is not less than α when measured with P is given as

$$\int_{S|_{P(S) \geq \alpha}} 1_S dP.$$

Mean Information

The mean information of all events of S is

$$\int_S -\log(P) dP.$$

When P is binarized with a certain threshold value with respect to the occurrence probability $P(s)$ of the element $s \in S$, the mean information is redefined as follows, on a newly binarized probability measure P' on the measurable space (S, \mathbf{E}, P') :

$$\int_S -\log(P') dP'.$$

Mean Yield Per Surface

The mean yield per surface on S can be defined by constituting a yield function $Y: S \rightarrow \mathbf{R}$, such as

$$\int_S Y dP.$$

The mean yield of vegetation with a yield above a certain value β , such as $Y \geq \beta$, is given as

$$\int_{S|Y(S) \geq \beta} Y dP.$$

If $Y(S)$ is a skewed distribution with respect to S , such as power-law distribution, attention should be paid to interpretation since the fluctuation of mean yield could be enormous in actual data.

Occurrence Probability of Objective Function

To obtain the occurrence probability of vegetation having an objective function $O: S \rightarrow \mathbf{R}$ greater than or equal to the constant value β , the measure space (S, \mathbf{E}, O) of the objective function should be constructed on the same completely additive class \mathbf{E} as (S, \mathbf{E}, P) , and given by

$$\int_{S|O(S) \geq \beta} 1_S dP.$$

Example: For tagged ecosystem data, the occurrence probability of various combinations of tags can be calculated. In order to handle co-occurrence of tags, it is necessary to construct a completely additive class \mathbf{E} of resolution that satisfies $s_i \cap s_j = \emptyset (s_i, s_j \in S)$.

Conditional Probability

If the two objective functions O_1 and O_2 are constructed as the measure $O_1: S \rightarrow \mathbf{R}$ and $O_2: S \rightarrow \mathbf{R}$ on the completely additive class \mathbf{E} of S , the integral of the target measure O_2 under the condition $A = \{s \in S | O_1(s) \geq \beta\}$ is given by

$$\int_A 1_S dO_2.$$

Calculation of Expected Value of an Objective Function by Non-uniform Probability Density Function

The expected value of the objective function $O(s)$ with respect to the non-uniform probability density function $P(s)$ on $s \in S$ is given as

$$\int_S O(s) dP = \int_S O(s) f(s) d\mu(s).$$

where $f: S \rightarrow \mathbf{R}$ is the probability density function of P for μ , which is called the Radon–Nikodym derivative. The set measure μ is, for example, $\mu(s) = \#\{s\}$ in case of a symbolic set.

On Vegetation Succession: Perron–Frobenius Operator and Climax Community

The vegetation transition can be represented as a symbolic dynamical system that is the temporal change of the direct product space $\mathbf{R}^m \times \mathbf{Str}^n$ of numerical (\mathbf{R}) and symbolic (\mathbf{Str}) data of soil and vegetation variables. Then, as an example, the climax community can be described using the Perron–Frobenius operator of the symbolic dynamical system. For simplicity, we consider a symbolic dynamical system T of n kinds of plant species on a two-dimensional map, as a model of vegetation succession:

$$T: \mathbf{R}^2 \times \mathbf{Str}^n \rightarrow \mathbf{R}^2 \times \mathbf{Str}^n,$$

where T is a non-singular map. If we want to include other numerical data \mathbf{R}^m such as environmental parameters, this extends to

$$T: \mathbf{R}^2 \times \mathbf{R}^m \times \mathbf{Str}^n \rightarrow \mathbf{R}^2 \times \mathbf{R}^m \times \mathbf{Str}^n.$$

Let V be a completely additive class on $X: \mathbf{R}^2$. V corresponds to a list of every niche structure of vegetation with real-value (infinite) resolution. Let $g(X)$ be the density function on X (Radon–Nikodym derivative). Practically, in case of a map which displays only the presence or absence of vegetation in practice, $g(X)$ is a binary function.

Here, we call the PF that is defined as follows for the Lebesgue measure m on X as the Perron–Frobenius operator of vegetation succession T .

$$\int_V \text{PF} \cdot g(x) dm = \int_{T^{-1}(V)} \text{PF} \cdot g(x) dm.$$

The stationary density function satisfying $\text{PF} \cdot g = g$ gives the area of each species that potential natural vegetation (climax community) comprises.

Practically, in consideration of intrinsic fluctuations, if the following relation holds with respect to the function norm of $\text{PF} \cdot g = g$ and the upper bound δ of fluctuation, the vegetation can be judged as climax community for a time scale t and inherent fluctuation δ :

$$|\text{PF}^t \cdot g - g| \leq \delta.$$

This relationship can also represent a stabilized monoculture method by human control, as detailed in Sect. 1.4.

If Perron–Frobenius operator PF for vegetation succession T can be completely determined, the potential natural vegetation and the response to the vegetation strategy of synecological farming can be uniformly described. In practice, since the real ecosystem is too complex to model as a dynamical system, the stationary density function that determines the Perron–Frobenius operator can only be numerically

approximated by the convergence of the function norm under inevitable fluctuation. Therefore, it can be described as a dynamical system of conditional probability, and it becomes necessary to connect to probabilistic analysis such as information geometry (Funabashi 2017b). By interpreting vegetation succession T and corresponding Perron–Frobenius operator PF as a probability map, finding deterministic structure as much as possible from these can be considered as the primary direction of model refinement.

Appendix 2: Food Self-sufficiency Measure with a Geometric Mean

The conventional definition of food self-sufficiency rate (SSR) is based on the arithmetic mean, whether it be calorie-based or production-based (FAO 2001). As an application of the concept of selective information developed in Sect. 1.4, we simulate a novel food self-sufficiency rate related to the geometric mean.

The problem of arithmetic means is that it does not correctly reflect the notion of self-sufficiency with respect to the diversity of food products: Suppose there exist food items that cannot be produced in a social community but crucial for the survival. Then, the community could not survive when the importation is prohibited, even if the total SSR over the whole food products is superior to 100%. This is typically the case with food production in limited geographical scale such as in small island (Hashiguchi 2005).

To properly adopt the notion of self-sufficient “ability” with respect to the survival of a community in isolation, the following geometric mean I_g can provide a simple definition of risk that threatens self-sufficiency regarding the diversity of food products:

$$I_g := \sqrt[k^{max}]{\prod_{k=1}^{k^{max}} l(SSR_k)},$$

where SSR_k is the SSR defined with the percentage of k -th food item ($k = 1, \dots, k^{max}$), and to cut above 100% of each SSR_k ,

$$l(x) := \begin{cases} 1 & \text{if } x \geq 100\% \\ 0.01 \cdot x & \text{else} \end{cases}$$

It transforms to the mean selective information I_s if we measure the self-sufficiency risk as a mean information cost for the search, such as

$$I_s := -\log\left(I_g^{k^{max}}\right) / k^{max} = -\log\left(\prod_{k=1}^{k^{max}} l(SSR_k)\right) / k^{max}$$

$$= - \sum_{k=1}^{k^{max}} \log l(SSR_k)/k^{max}.$$

The mean selective information I_s represents the mean information cost to search all food products under given SSR. It diverges to infinity when there is a single food item with $SSR_k = 0\%$, while coincides with 0 when all food items' $SSR_k = 100\%$. It represents the situation that there exists sufficient food in the world, but the distribution is not equitable for the self-sufficiency of the global population (FAO 2011).

Actual trade of food products between and within social communities may substitute some items with others. We define a natural extension of the mean selective information I_s to the domain including $SSR_k > 100\%$, as the extended mean selective information I'_s :

$$I'_s = - \sum_{k=1}^{k^{max}} \log l'(SSR_k)/k^{max},$$

where

$$l'(x) := 0.01x.$$

This formulation is equivalent to define the exchange rate of a product with others according to the ratio of selective information representing the search cost. For the value $SSR_k > 100\%$, the selective information turns into a negative value and can be interpreted as a search gain that cancels out the search cost of other products.

We simulated the I_s and I'_s for the different levels of production from power-law vegetation. The algorithm is defined as follows:

1. Define the parameters a and b of Pareto distribution (see Sect. 1.2).
2. Sample k^{max} values from the Pareto distribution and define them as $p_k (k = 1, \dots, k^{max})$.
3. Create a new series $p'_{k_1 k_2}$ with respect to each value of p_k as a regularization factor, such as $p'_{k_1 k_2} := p_{k_1}/p_{k_2} (k_1, k_2 = 1, \dots, k^{max})$.
4. Calculate I_s and I'_s for each k_2 with respect to $k_1 = 1, \dots, k^{max}$, with the use of $SSR_{k_1 k_2} = 100 \cdot p'_{k_1 k_2}$. For each k_2 , the number of $SSR_{k_1 k_2}$ that exceeds 100% should be attributed as $\#\{SSR_{k_1 k_2} | SSR_{k_1 k_2} \geq 100\%, k_1 = 1, \dots, k^{max}\}$, which can be simplified to a single parameter k such as $\#\{SSR_k \geq 100\%\}$ ($k = 1, \dots, k^{max}$).
5. Repeat from 2 to 4 for N_s times and take the mean values and standard deviations of I_s and I'_s for each k_2 with respect to N_s samplings.

The results are shown in Fig. 1.14. As a representative example, $k^{max} = 120$ was chosen to represent the commonly utilized crop species diversity in world agriculture (Yong et al. 2006). $N_s = 193$ corresponds to the number of member states of the United Nations (UN 2017). Naturally from the definition, the value of I_s converges

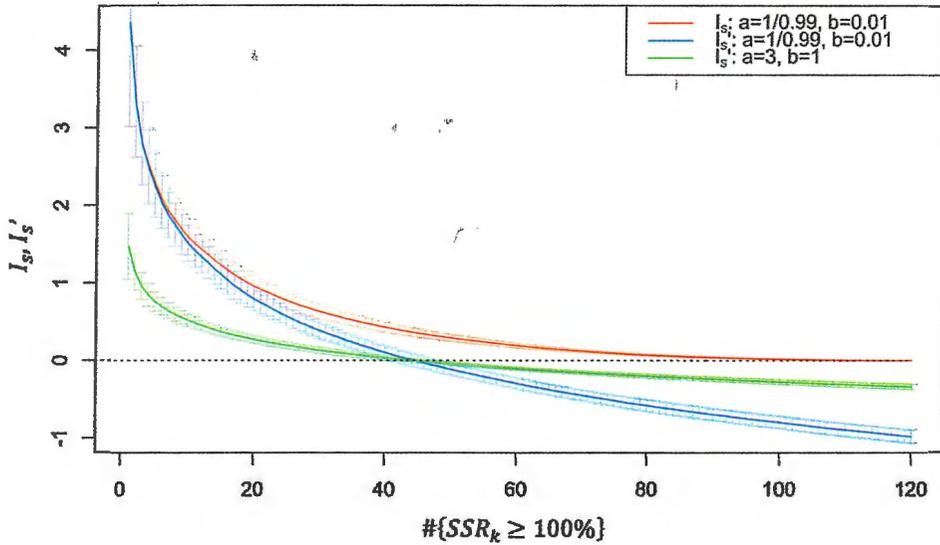


Fig. 1.14 Simulation of the mean selective information I_s and the extended mean selective information I'_s with respect to the number of self-sufficient food products $\#\{SSR_k \geq 100\%$ ($k = 1, \dots, k^{max}$). Mean \pm standard deviation of I_s and I'_s is shown with the red and blue plot, respectively, and those of I'_s with the green plot. The value of $\#\{SSR_k \geq 100\%$ where I'_s crosses zero (intersection between blue and green lines) is shown to be invariant with respect to different values of parameters a and b that define Pareto distribution

to zero as the number of self-sufficient crops approaches to k^{max} , since all food products need to achieve self-sufficiency for the survival. On the other hand, I'_s admits the compensation between crops by the extended definition of search cost, which achieves self-sufficiency risk zero around $\#\{SSR_k \geq 100\% \} = 44$ to 45. This critical value is invariant with the parameters of power-law vegetation a and b , due to the logarithmic property of selective information and regularization process of the algorithm.

This simulation suggests that the self-sufficient ability defined with respect to the risk index I'_s can be achieved by securing SSR of about 37% of the necessary product diversity within a closed territory if we take on the strategies of adaptive diversification with power-law productivity. By exchanging k^{max} and N_s in the algorithm, we can simulate the case of international trades between N_s countries (following power-law productivity) with variance on k^{max} crop diversity, which derives qualitatively the same behavior of I'_s : 37% of the member states need to achieve self-sufficiency for each crop, in order to attain global sufficiency under the exchange rate defined in I'_s .

Parameters: The values of a and b are shown in the figure legend. $k^{max} = 120$, $N_s = 193$.

Appendix 3: Ecological Scarcity and Land Utilization

How can we most efficiently allocate the land use distribution (e.g., between city, farmland, and protected area) for the protection of biodiversity? For that purpose, let us think about the ecological value of a species. The value of a species in ecosystems has multi-faceted criteria, over multiple ecosystem functions and services, on various spatial-temporal scales. There is an only limited amount of known value compared to the unknown part that cannot be measured advance. Take for example ecological resilience, there could be an infinite unknown possibility of ecological disturbance in the future in which each species may play constructive roles for the recovery and development of new ecosystems.

An indeterminable amount of our ignorance primarily limits the argument on resilience. If we are to formulate the total amount of functions and these values of a species with respect to the future resilience of ecosystems, an only expression such as “all species are equally invaluable at the largest limit of spatial-temporal scale” would be allowed to eliminate any specific bias. We call this premise as the “**value equivalence principle of species,**” which mathematical formulations commonly adopt for multiple diversity indexes in ecological study. This standpoint is also vital in the management process of one-time-only events such as natural disasters, in which we need to select a fail-safe strategy without prior knowledge of future change (Funabashi 2017c).

Now, suppose that all species are equally invaluable for a whole ecosystem. The simplest ideal scenario of the conservation is to allocate each species an equal surface, or uniform distribution of habitat surface over species, which maximizes Shannon’s diversity index measured on the proportion of habitats. The actual distribution of species would differ under multiple social and ecological factors, which can be quantified with the following measure of ecological scarcity R_k of a species k :

$$R_k = \frac{C}{X_k},$$

where X_k is the habitat surface of the species k , and C is the total surface taking arbitrary constant value. Here, ecological scarcity R_k represents how much a species deserves conservation value with respect to the smallness of actual habitat under the value equivalence principle of species.

Let us consider the fractal dynamics of niche differentiation. For simplicity, we consider the recurrence relation of one-dimensional Cantor set¹¹ f_c as follows, which divides the surface C represented as a line segment into two isometric parts:

$$C_n = f_c(C_{n-1}) = \frac{C_{n-1}}{3} \cup \left(\frac{2}{3} + \frac{C_{n-1}}{3} \right)$$

¹¹Three-dimensional generalization of the Cantor set is the Menger sponge discussed in Sect. 1.3 as an essential model of niche differentiation.

for $n \geq 1$, and $C_0 = [0, C]$.

This means that by deleting the open middle third $(C/3, C/3)$ from the interval $[0, C]$, this transformation leaves two line segments: $[0, C/3]$ and $[2C/3, C]$.

After n iteration of f_c , the habitat X_k will divide into 2^n separated niches, and the ecological scarcity becomes

$$R_k \doteq \left(\frac{3}{2}\right)^n.$$

To avoid parameter dependency, we normalize the niche surface ratio of a species k by dividing X_k with C as

$$\frac{X_k}{C} = \left(\frac{2}{3}\right)^n.$$

The relationship between the number of different niches, its surface ratio, and ecological scarcity of a species is depicted in Fig. 1.15. Starting from a monoculture situation, as niche differentiation progresses with n and increases the complexity of fractal configuration (Fig. 1.15 left), ecological scarcity increases in an exponential manner (Fig. 1.15 right).

Such situation is particularly familiar with rapidly expanding urban land use planning, where complex intersections with multi-fractal features between city, farmland, and natural ecosystems are often at the forefront of the development (e.g., Wu et al.

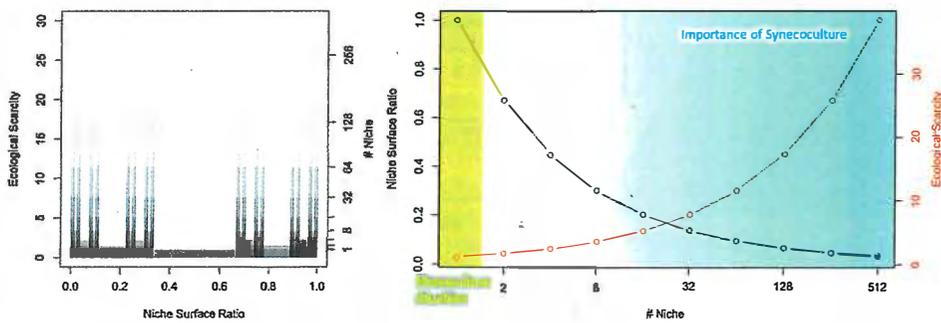


Fig. 1.15 Relationship between niche surface ratio X_k/C , ecological scarcity R_k , and niche number 2^n of a species k after n -time niche differentiation with recurrence relation f_c . **Left** Niche partitions on the scale of surface ratio versus ecological scarcity R_k . The gray rectangles that correspond to the direct product sets $\frac{C_n}{C} \times [0, R_k]$ are superimposed for different $n = \{0, 1, 2, \dots, 9\}$. The intervals C_n/C correspond to the niche partitions after n -th iteration measured on the scale of niche surface ratio on X -axis. The number of differentiated niches is aligned at right Y -axis in correspondence with the value of R_k in left Y -axis. **Right** Number of niche partitions 2^n versus niche surface ratio X_k/C and ecological scarcity R_k . As the niche number increases with n , niche surface ratio decreases, and ecological scarcity increases in an exponential manner. Monoculture situation (yellow background) is dominated by a single species with low ecological scarcity, while highly differentiated mixed polyculture situations (cyan background) consist of niches with high ecological scarcity, where the role of synecoculture on the conservation efforts becomes increasingly important

2013). In finely fragmented lands with various heterogenic environments, conventional monoculture farming methods are inefficient to perform, while synecoculture can provide combined solutions by making use of the particularity of each niche condition with various vegetation portfolios, and combining with other modes of food production according to the adjacent land use that provides different accessibility for the distribution of the products. This strategy can harmonize the conservation of rare species with high ecological scarcity and small-scale local production of various food products in the burgeoning frontiers of urban development. To raise awareness and increase susceptibility to synecoculture, practices in small-scale fragmented land such as family gardens, abandoned farmland, and city greenbelt are important, which will strengthen the future option of environmental conservation in smart green cities. Figure 1.16 left shows a schematic diagram of the patterns of the combination of synecoculture with other adjacent land use. Not only the in-field strategy of adaptive diversification in synecoculture (Sect. 1.4, Fig. 1.4), we can also produce local food from surrounding practices and environments, such as conventional agriculture, urban farming, and hunting-gathering. In either case, coping with small-scale diversified practices are strongly influenced by power-law fluctuation, which needs to count on the stability of harmonic mean for the management (Fig. 1.16 right, see also Sect. 1.4). To realize human augmentation of ecosystems at the boundaries between city and natural environments, we need to deeply understand these properties of the

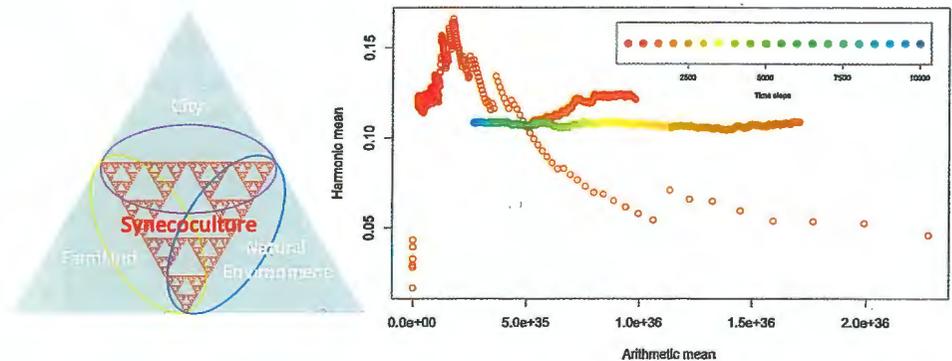


Fig. 1.16 **Left** Synecoculture as an interface between urban and natural environments. Conceptual diagram of growing margins at the intersections between city, farmland, and natural environment is depicted as self-organized fractal landscape (red triangles), where synecoculture can play an important role for both conservation of ecologically scarce species and local food production. According to the adjacent land use, synecoculture can be combined with 1. conventional agriculture (yellow circle); 2. urban farming (violet circle); and 3. hunting-gathering activities (blue circle) in the mixed topography. **Right** Convergence of harmonic mean and divergence of arithmetic mean in Pareto distribution. Ten thousand independent samplings were performed from a Pareto distribution with $a = 0.1$ (i.e., no finite arithmetic mean, see Sect. 1.2), $b = 0.01$. The dynamics of the arithmetic mean of previous samplings (horizontal axis) show huge discontinuous fluctuation several times triggered by rare big events, while that of the harmonic mean (vertical axis) is confined in a small stable range and converges through time. Color gradient represents the time step of the sampling

power law prevalent in urban and vegetation dynamics and presuppose the benefits to both sides in the formation of public opinions and policymaking.

Mathematical proof for the convergence of the harmonic mean of Pareto distribution is given as follows:

For a harmonic mean $H(X)$ of $f(x) = \frac{ab^a}{x^{a+1}}$, ($x \in X := (b, \infty]$) in Sect. 1.2,

$$\begin{aligned} \frac{1}{H(X)} &= \int_{-\infty}^{\infty} \frac{1}{x} f(x) dx \\ &= \int_b^{\infty} \frac{ab^a}{x^{a+2}} dx \\ &= \frac{ab^a}{a+1} \left[-x^{-(a+1)} \right]_b^{\infty} \quad (a \neq -1). \end{aligned}$$

Then, the condition that the right side does not diverge to infinity is given by

$$-(a+1) < 0,$$

$$a > -1$$

By definition, $a > 0$, then for all $a > 0$, $1/H(X)$ converges to a finite value as follows:

$$\begin{aligned} \frac{1}{H(X)} &= \frac{ab^a}{a+1} \{0 - (-b^{-(a+1)})\} \\ &= \frac{a}{(a+1)b}, \end{aligned}$$

which gives

$$H(X) = \frac{b(a+1)}{a}.$$

References

- Akasaka M, Kadoya T, Ishihama F et al (2017) Smart protected area placement decelerates biodiversity loss: a representation-extinction feedback leads rare species to extinction. *Conserv Lett* 10(5):539–546
- Albert CH, de Bello F, Boulangeat I et al (2012) On the importance of intraspecific variability for the quantification of functional diversity. *Oikos* 121:116–126
- Anderson C (2008) *The long tail*. ISBN 9781401387259
- Arrhenius O (1921) Species and area. *J Ecol* 9:95–99

- Barnosky AD, Hadly EA, Bascompte J et al (2012) Approaching a state shift in Earth's biosphere. *Nature* 486:52–58
- Bastian M, Heymann S, Jacomy M (2009) Gephi: an open source software for exploring and manipulating networks. International AAAI Conference on Weblogs and Social Media. <https://www.aaai.org/ocs/index.php/ICWSM/09/paper/view/154/1009>
- Cadotte MW, Carscadden K, Mirotchnick N (2011) Beyond species: functional diversity and the maintenance of ecological processes and services. *J Appl Ecol* 48:1079–1087
- Carmona CP, Guerrero I, Morales MB et al (2017) Assessing vulnerability of functional diversity to species loss: a case study in Mediterranean agricultural systems. *Funct Ecol* 31:427–435
- Convention on Biological Diversity (CBD) (2000) The Cartagena protocol on biosafety to the convention on biological diversity. <https://www.cbd.int/doc/legal/cartagena-protocol-en.pdf>
- Convention on Biological Diversity (CBD) (2010a) The Nagoya protocol on access to genetic resources and the fair and equitable sharing of benefits arising from their utilization (ABS) to the convention on biological diversity
- Convention on Biological Diversity (CBD) (2010b) Aichi biodiversity targets. <https://www.cbd.int/sp/targets/>
- Convention on Biological Diversity (CBD) (2017) The access and benefit-sharing clearing-house. <https://absch.cbd.int/>
- Crutzen PJ (2002) Geology of mankind. *Nature* 415:23. <https://doi.org/10.1038/415023a>
- Cushing JM, Costantino RF, Dennis B et al (2005) Chaos in ecology experimental nonlinear dynamics, vol 1. Theoretical ecology series. Academic Press. ISBN 978-0-12-198876-0
- de Bello F, Lavorel S, Albert CH et al (2011) Quantifying the relevance of intraspecific trait variability for functional diversity. *Methods Ecol Evol* 2:163–174
- DGM (Dedicated Grant Mechanism for Indigenous Peoples and Local Communities) (2017) Annual report. https://static1.squarespace.com/static/550abd2ce4b0c5557aa4f772/t/5a26f29b085229c33332f339/1512501925869/DGM_Report_Annual-2017_LR_EN.pdf
- FAO (Food and Agriculture Organization) (2001) Food balance sheets a handbook. <http://www.fao.org/docrep/003/X9892E/X9892E00.htm#TopOfPage>
- FAO (Food and Agriculture Organization) (2011) Global food losses and food waste. <http://www.fao.org/docrep/014/mb060e/mb060e00.pdf>
- FAO (Food and Agriculture Organization) (2016) FAO guideline: voluntary guidelines for mainstreaming biodiversity into policies, programmes and national and regional plans of action on nutrition. <http://www.fao.org/3/a-i5248e.pdf>
- Farrion CE, Bohlman SA, Hubbell S et al (2016) Dominance of the suppressed: power-law size structure in tropical forests. *Science* 351:155–157
- Flynn DFB, Mirotchnick N, Jain M et al (2011) Functional and phylogenetic diversity as predictors of biodiversity-ecosystem-function relationships. *Ecology* 92:1573–1581
- Funabashi M (2013) IT-mediated development of sustainable agriculture systems-toward a data-driven citizen science. *J Inf Technol Appl Educ* 2(4):179–182
- Funabashi M (2016a) Synecological farming: theoretical foundation on biodiversity responses of plant communities. *Plant Biotechnol* 33:213–234
- Funabashi M (2016b) Synecoculture manual 2016 version (English version). Research and Education material of UniTwin UNESCO Complex Systems Digital Campus, e-laboratory: Open Systems Exploration for Ecosystems Leveraging, No. 2
- Funabashi M (2016c) Chapter 4.1. In: Tokoro M, Takahashi K (eds) Water cycle and life: creating water environment in 21st century. [Mizu daijunkan to kurashi: 21 seiki no mizu kankyo wo tsukuru (in Japanese)]. Maruzen Planet, Japan, pp 95–112
- Funabashi M (2017a) Synecological farming for mainstreaming biodiversity in smallholding farms and foods: implication for agriculture in India. *Indian J Plant Genet Resour* 30(2):99–114. <https://doi.org/10.5958/0976-1926.2017.00016.X>
- Funabashi M (2017b) Citizen science and topology of mind. *Entropy* 19(4). <https://doi.org/10.3390/e19040181>

- Funabashi M (2017c) Open systems exploration: an example with ecosystems management. First Complex Systems Digital Campus World E-Conference, vol 2015, pp 223–243
- Funabashi M, Hanappe P, Isozaki T et al (2017) Foundation of CS-DC e-laboratory: open systems exploration for ecosystems leveraging. First Complex Systems Digital Campus World E-Conference, vol 2015, pp 351–374
- GLOBI (2017) <https://www.globalbioticinteractions.org>
- Guimarães PR Jr, Pires MM, Jordano P et al (2017) Indirect effects drive coevolution in mutualistic networks. *Nature* 550:511–514
- Hashiguchi Y (2005) Islands need “food self-sufficiency ability”. *J Island Stud* 2005(5):33–53
- Houlton BZ, Morford SL, Dahlgren RA (2018) Convergent evidence for widespread rock nitrogen sources in Earth’s surface environment. *Science* 360:58–62
- Jaenicke H, Ganry J, Hoeschle-Zeledon I et al (eds) (2009) International symposium on underutilized plants for food security, nutrition, income and sustainable development. Arusha, Tanzania. ISBN 978-90-66057-01-2
- Larkin DL, Bruland GL, Zedler JB (2016) Heterogeneity theory and ecological restoration. In Palmer MA, Zedler JB, Falk DA (eds) *Foundations of restoration ecology*. Island Press. ISBN 9781610916974
- Laurance WF (2009) Beyond island biogeography theory. In: Losos JB, Ricklefs RE (eds) *The theory of island biogeography revisited*. Princeton University Press, United States, pp 214–236
- Laurance W, Mesquita R, Luizão R et al (2004) The biological dynamics of forest fragments project: 25 years of research in the Brazilian Amazon. *Tropinet* 15(2/3):1–3
- McCab (2017) <http://taku910.github.io/mecab/>
- Nayak C (2008) Comparing various fractal models for analyzing vegetation cover types at different resolutions with the change in altitude and season. Master Thesis, Faculty of Geo-Information Science and Earth Observation of the University of Twente (ITC), Enschede, the Netherlands, and Indian Institute of Remote Sensing (IIRS), National Remote Sensing Agency (NRSA), Department of Space, Dehradun, India. http://www.iirs.gov.in/iirs/sites/default/files/StudentThesis/chandan_final.pdf
- NRC (National Research Council) (1993) *Managing global genetic resources: agricultural crop issues and policies*. The National Academies Press, Washington, DC. <https://doi.org/10.17226/2116>
- Paroda RS, Tyagi RK, Mathur PN et al (eds) (2017) Proceedings of the ‘1st international agrobiodiversity congress: science, technology and partnership’, New Delhi, India, November 6–9, 2016. Indian Society of Plant Genetic Resources, New Delhi and Bioersity International, Rome, 152 pp
- Pecl GT, Araújo MB, Bell JD et al (2017) Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 355. <https://doi.org/10.1126/science.aai9214>
- Pereira HM et al (2010) Scenarios for global biodiversity in the 21st century. *Science* 330:1496. <https://doi.org/10.1126/science.1196624>
- Petherick A (2012) A note of caution. *Nat Clim Change* 2:144–145
- Prusinkiewicz P, Lindenmayer A (2012) *The algorithmic beauty of plants*. Springer, ISBN 9781461384762
- Putman RJ, Wratten SD (1984) *Principles of ecology*. University of California Press, California
- R Core Team (2015) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>
- Reich PB, Tilman D, Isbell F et al (2012) Impacts of biodiversity loss escalate through time as redundancy fades. *Science* 336:589–592
- Reuter MA, Hudson C, Hagelüken C et al (2013) *Metal recycling: opportunities, limits, infrastructure*. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. UNEP
- Richards CM, Falk DA, Montalvo AM (2016) Population and ecological genetics in restoration ecology. In Palmer MA, Zedler JB, Falk DA (eds) *Foundations of restoration ecology*. Island Press, ISBN 9781610916974

- Rippke U, Ramirez-Villegas J, Jarvis A et al (2016) Timescales of transformational climate change adaptation in sub-Saharan African agriculture. *Nat Clim Change* 6:605–609
- Rohde RA, Muller RA (2005) Cycles in fossil diversity. *Nature* 434:208–210
- Scanlon TM, Caylor KK, Levin SA et al (2007) Positive feedbacks promote power-law clustering of Kalahari vegetation. *Nature* 449:209–212
- Seuront L (2010) *Fractals and multifractals in ecology and aquatic science*. CRC Press. ISBN 9781138116399
- Steffen W, Richardson K, Rockström J et al (2016) Planetary boundaries: guiding human development on a changing planet. *Science* 347:1259855
- Takayasu H, Sato A, Takayasu M (1997) Stable infinite variance fluctuations in randomly amplified Langevin systems. *Phys Rev Lett* 79:966–969
- TINA (2017) <https://iscpif.fr/chavalarias/projects/tinasoft/>
- Tindano A, Funabashi M (eds) (2016) *Proceedings of the 1st African forum on synecoculture (English version)*. Research and Education material of UniTwin UNESCO Complex Systems Digital Campus, e-laboratory: Open Systems Exploration for Ecosystems Leveraging, No. 5
- Tindano A, Funabashi M (eds) (2017) *Proceedings of the 2nd African forum on synecoculture (English version)*. Research and Education material of UniTwin UNESCO Complex Systems Digital Campus, e-laboratory: Open Systems Exploration for Ecosystems Leveraging, No. 7
- Turner GM (2008) A comparison of the limits to growth with 30 years of reality. *Glob Environ Chang* 18(3):397–411
- UA (African Union) (2015) *Lignes directrices pratiques de l'Union Africaine pour la mise en oeuvre coordonnée du Protocole de Nagoya en Afrique*. http://www.abs-nitiative.info/fileadmin/media/Knowledge_Center/Pulications/African_Union_Guidelines/UA_Lignes_Directrices_Pratiques_Sur_APA_-_20150215.pdf
- UN (United Nations) (2015) Sustainable development goals. <https://sustainabledevelopment.un.org/sdgs>
- UN (United Nations) (2017) UN member states. <https://www.un.org/depts/dhl/unms/whatisms.shtml>
- UNEP (United Nations Environment Programme) (2017) <http://web.unep.org/regionalseas/what-we-do/conservation-biodiversity-areas-beyond-national-jurisdiction-bbnj>
- Whittaker RH (1960) Vegetation of the Siskiyou mountains, Oregon and California. *Ecol Monogr* 30:280–338
- Wu H, Sun Y, Shi W et al (2013) Examining the satellite-detected urban land use spatial patterns using multidimensional fractal dimension indices. *Remote Sens* 5:5152–5172. <https://doi.org/10.3390/rs5105152>
- Yong RN, Mulligan CN, Fukue M (2006) *Geoenvironmental sustainability*. CRC Press, United States
- Zuppinger-Dingley D, Schmid B, Petermann JS et al (2014) Selection for niche differentiation in plant communities increases biodiversity effects. *Nature* 515:108–111