ウェブサイト公開用

（様式 10）
（海外特別研究員事業）
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海 外 特 別 研 究 員 最 終 報 告 書

独立行政法人日本学術振興会 理事長　殿

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受 付 番 号　201860745
氏　　　　名　梁 政寛
（氏名は必ず自署すること）

海外特別研究員としての派遣期間を終了しましたので、下記のとおり報告いたします。
なお、下記及び別紙記載の内容については相違ありません。

記

1. 用務地（派遣先国名）用務地：　ベルリン　（国名：　ドイツ　）

2. 研究課題名（和文）※研究課題名は申請時のものと違わないように記載すること。
生態圏水文学：陸域植物と微生物が流域水循環に及ぼす影響の解明と水資源管理への応用

3. 派遣期間：平成　31　年　2　月　28　日　～　令和　2　年　1 月　31 日

4. 受入機関名及び部局名
Freie Universität Berlin, Institute of Biology

5. 所期の目的の遂行状況及び成果…書式任意　**書式任意（A4 判相当 3 ページ以上、英語で記入も可）**
（研究・調査実施状況及びその成果の発表・関係学会への参加状況等）
（注）「6. 研究発表」以降については様式 10－別紙 1～4 に記入の上、併せて提出すること。

所期の目的の遂行状況及び成果

Masahiro Ryo

Recent biological studies have revealed that terrestrial plants and their associations with soil microorganisms are a major biological forcing of soil structuring, which in turn, influence the hydrological properties of surface soil. Their hydrological contributions, however, are mostly overlooked in the current hydrological study. The proposed research aimed primarily (i) to evaluate the importance of the contributions by plants and soil microorganisms on hydrological properties of soil, (ii) to elucidate the mechanisms, and (iii) to integrate their roles as ecosystem service into water resources management. I have mostly achieved the first and second aims and partially the third one. Within the period of the scholarship (about 1 year), as a result, I published 5 articles, including in Science (as co-first author) and Trends in Ecology and Evolution (the highest JIF in the field of ecology). I was also nominated for a young career award by the Ecological Society of Japan. Overall, I would assess my own performance exceptional. Since the topic is promising, I would continue it and expand the scope further in my future career.

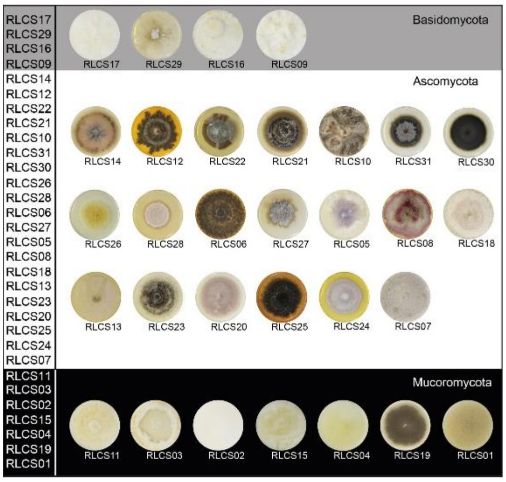

Figure 1. The 31 saprobic fungal strains comprising members of the phyla Ascomycota, Basidiomycota, and Mucoromycota are shown (4 week old colonies).

Main finding 1: Filamentous saprobic fungi, especially ones with dense hyphae, contribute largely making soil particle larger. Thus, fungi affects soil water property.

Soil structure, the complex arrangement of soil into aggregates and pore spaces, is a key hydrological feature of soil. Among soil biota, filamentous saprobic fungi have well-documented effects on soil aggregation. However, it is unclear what properties, or traits, determine the overall positive effect of fungi on soil aggregation. To achieve progress, it would be helpful to systematically investigate a broad suite of fungal species for their trait expression and the relation of these traits to soil aggregation.

In Lehmann et al. (2020, published in *Frontiers in microbiology*), we applied a trait-based approach to a set of 15 traits measured under standardized conditions on 31 fungal strains including Ascomycota, Basidiomycota, and Mucoromycota, all isolated from the same soil (**Fig. 1**). We found large differences among these fungi in their ability to aggregate soil, including neutral to positive effects, and we documented large differences in trait expression among strains (**Fig. 2A**).

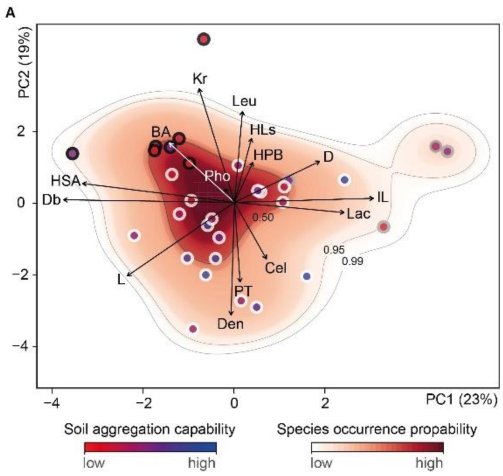

Figure 2. (A) Relationships between traits of fungal strains and soil aggregation capability.

We identified biomass density, i.e., the density with which a mycelium grows (positive effects), leucine aminopeptidase activity (negative effects) and phylogeny as important factors explaining differences in soil aggregate formation (SAF) among fungal strains. Importantly and counterintuitively, growth rate was not among the important traits (**Fig. 2B**).

Our results point to a typical suite of traits characterizing fungi that are good soil aggregators. In an applied context of hydrology, such trait information can inform soil water properties. Even though we here focused on saprobic soil fungi, some aspects may also be generalizable to other fungal groups. For example, future work should test if hyphal density is also a better predictor for soil aggregation ability than hyphal biomass production in arbuscular mycorrhizal fungi.

We also considered the role of shape in soil aggregation structuring as powerfully illustrated by fungi as well as microplastic particles in the environment. In soil, naturally occurring primary particles, like sand, silt, and clay, are irregularly shaped or roughly spherical, bacteria are spherical or rod-shaped, fungal hyphae are branched linear objects. When adding microplastics of roughly similar shape to the particles already present, for example spherical particles or fragments, they might behave like primary particles. However, there are other shapes, such as films and fibers that diverge in form from existing particles. In Rillig et al. (2019; published in *Environmental Science & Technology*), we proposed that a similar shape of microplastic and fungi hyphae can potentially own a similar effect to soil aggregation capacity.

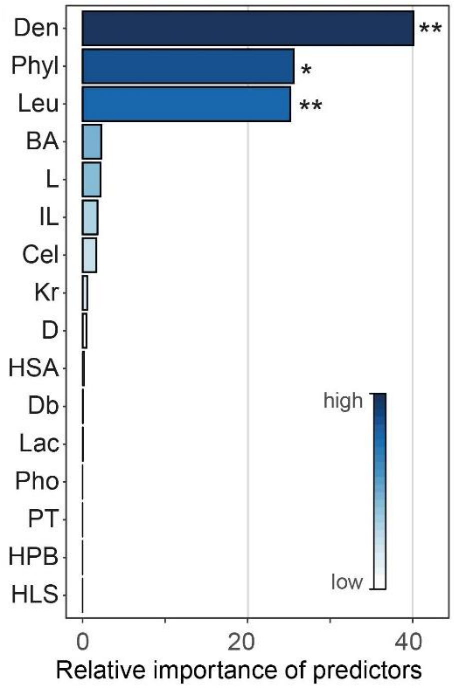

Figure 2. (B) Identifying fungal hyphal density as a key trait explaining soil aggregation capability, using a random forest machine learning algorithm.

Major finding 2: Soil becomes surprisingly water-repellent (i.e. soil does not allow water infiltration) when soil microbial organisms including filamentous saprobic fungi are attacked by several environmental problems including climate change effect.

Global environmental change is driven by multiple natural and anthropogenic factors. With a focus on global change as it affects soils, Rillig and Ryo *et al.* (2019, Ryo as a co-first author; published in *Science*) point out that nearly all published studies consider just one or two factors at a time. In a laboratory experiment, we tested 10 drivers of global change both individually and in combination, at levels ranging from 2 to 10 factors.

At the single-factor level, some factors had neutral, negative, or positive effects on a number of key responses, which included soil aggregation (a key component of soil structure), soil water repellency (water drop penetration time), decomposition, and soil respiration (**Fig. 3**). Soil aggregation and soil water repellency changed strongly with eight or more factors, and effects deviated from predictions, indicating synergistic interactions. Nonetheless, in agreement with our prediction, the changes in all response variables showed a consistent directional change with the number of factors included.

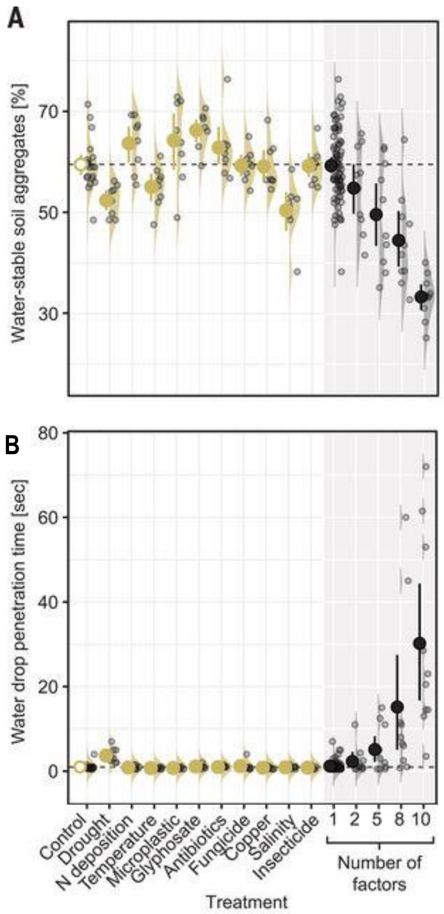

Figure 3. Soil particles become more fragile and less water penerable when many environmental problems attack soil microbes together.

We found that soil properties, processes, and microbial communities could not be predicted from single-effect responses and that multiple factors in combination produced unsuspected responses. We concluded that single-factor studies remain important for uncovering mechanisms but that global change biology needs to embrace more fully the multitude of drivers impinging on ecosystems. We are now testing the effect of plants in addition to microbes to complete one of the aims.

Major finding 3: Basic principles of temporal dynamics in ecology and evolution can be summarized in a hierarchically nested structure, and the structure needs to be considered to better understand the temporally dynamic interaction between soil microorganisms and soil-water properties.

In Ryo et al. (2019, published in Trends in Ecology and Evolution), we introduced basic principles of temporal dynamics in ecology. We figured out essential features that describe temporal dynamics by finding similarities among about 60 ecological concepts and theories. We found that considering the hierarchically nested structure of complexity in temporal patterns (i.e. hierarchical complexity) can well describe the fundamental nature of temporal dynamics by expressing which patterns are observed at each scale (**Fig. 4**). Across all ecological levels, driver–response relationships can be temporally variant and dependent on both short- and long-term past conditions. The framework can help with designing experiments, improving predictive power of statistics, and enhancing communications among ecological disciplines.

We proposed hierarchical complexity as a fundamental concept that describes temporal patterns of driver–response relationship, based on the collection of nearly 60 terms and concepts across subfields in ecology and evolution. We think that using this concept will advance ecology and evolution in two main ways. First, it provides a common language for better communication among ecologists studying analogous concepts in different subfields. Second, it stresses the need to consider past events for adequately considering the current and future state of ecological phenomena. Across all ecological levels, from individual to ecosystem, the ecological driver–response relationships can be temporally variant and dependent on both short- and long-term past conditions.

Such a conceptual generalization would ultimately help extending our major findings on the relationships between soil microorganisms and soil-water properties. Now, based on this conceptual framework, we are testing how multiple environmental changes occurring one by one can affect the traits of filamentous saprobic fungi, which are related to soil-water properites.

Major finding 4: As a hypothesis generated during this scholarship, managing biodiversity of soil and plant might enhance the potential of ecosystem services necessary for water resouces management. This hypothesis can be further studied in the future, based on the research network I have developed during the funding period.

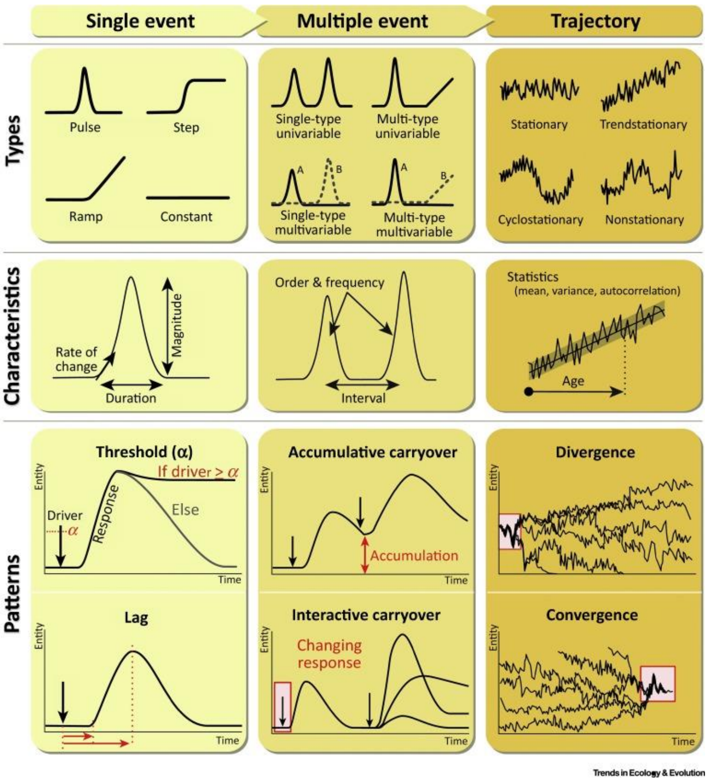

Figure 4. Basic Principles of Temporal Dynamics. At each level of complexity, some unique properties are summarized. At single-event level, for instance, there are four different types of patterns, three quantifiable characteristics, and two important nonlinear patterns. For all drawings, the horizontal axis is time and the vertical axis can be any measurable quantity. Driver and response are categorized by their shape based on type (upper panels), and their characteristics are quantitatively measurable (middle panels). By considering the combination of driver and response, driver–response relationships may give rise to some level-dependent patterns (lower panels).