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研究課題名（和文）気候変動に伴う河川生態系のリスク評価：統計モデルとメソコスム実験の融合

研究課題名（英文）Risk assessment of river ecosystems due to climate change: Integrating statistical models and mesocosm experiments

研究代表者

Ｇ・ＭＯＬＩＮＯＳ　ＪＯＲＧＥ（GARCIA MOLINOS, Jorge）

北海道大学・北極域研究センター・准教授

研究者番号：３０７６７２８１

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研究成果の概要（和文）：本プロジェクトの目的は、フィールドモニタリング、統計モデル、実験を用いて、気候変動が日本の河川とその生物多様性に及ぼすリスクを理解することである。複数流域の計数百地点を調査した結果、河川の水温変化に対して流域およびリーチスケールの変数の重要性が示唆された。特に火山性地質は、安定した低温環境を提供することで特異的な生物群集を形成した。将来シナリオを分析した結果、火山性河川は好適な温度条件を維持し、気候変動レフュージアとして機能すると予測された。今後生じうる温暖化および熱波を模倣した実験により、寒冷適応種の減少と水生食物網の崩壊が示されたため、レフュージアの利用可能性は重要になると考えられる。

研究成果の学術的意義や社会的意義
補完的な手法（フィールドモニタリング、モデル、実験）を組み合わせることにより、我々のプロジェクトは、将来の気候変動が日本の河川とその生物相に与えうる影響の大きさとタイプ、およびさまざまな環境・景観変数が河川内の温度環境にどのような影響を与えうるかについて、新規かつ頑健な知見を提供する。特に、地質の重要性を浮き彫りにし、将来的な気候変動において、火山性湧水を水源とする河川が安定した冷水環境を提供するレフュージアとして機能する可能性を示している。これらの結果を総合すると、本研究は、地質に基づく気候変動レフュージアを河川管理や保全計画に組み込むのに役立つ、斬新で重要な情報を提供する。

研究成果の概要（英文）：The aim of the project was to gain a better understanding of the risk from climate change to Japanese rivers and their biodiversity by combining field monitoring, statistical models and experiments. Using hundreds of monitoring sites across several catchments, we demonstrated the importance of catchment- and reach-scale variables in regulating stream water temperatures. In particular, volcanic geology, as a surrogate for cold groundwater inputs, was associated with stable cool habitats that sustained distinctive stream communities. Our analysis of future climate scenarios showed that these volcanic streams will retain suitable thermal conditions over the century acting as climate refugia. Availability of such refugia will be increasingly important as our experiments demonstrated that increasing warming trends and more frequent and severe heat waves, mimicking future projected regional conditions, will lead to a reduction of cold-adapted species and disrupted aquatic food webs.

研究分野：生態学

キーワード：気候変動　河川生態系　水温予測　種間関係　メソコスム実験

１．研究開始当初の背景

Climate change is expected to become a main driver of ecosystem and biodiversity change over the course of this century [1]. Climate change has already altered the abundance and distribution of species from land to oceans, resulting in the reshuffling of biodiversity across ecosystems, with far-reaching impacts on ecosystem functioning and human well-being [2, 3]. Existing research on the effects of climate change on biodiversity is strongly biased towards terrestrial and marine ecosystems despite freshwaters being disproportionately important as a resource (only 10% of the world's population lives further than 10 km away from freshwater [4], which fisheries provide the equivalent of all dietary animal protein for 158 million people globally [5]) and their very high ecological value (comprising less than 0.01% of the Earth' surface yet hosting an estimated 10% of all described species [6]). Further, their linear dendritic arrangement and insular nature make freshwater systems particularly exposed to the impacts of climate change, limiting severely compensatory movements by organisms into cooler habitats. Most existing studies only assess the effects of climate change from a species-level perspective, and there are many unknowns about how community structure and ecosystem function will change in the future as species distributions and environmental conditions change. Anticipating such responses is crucial for improving adaptive conservation and management.

２．研究の目的

This project integrates field monitoring, statistical models, and field manipulation experiments with the purpose to gain a robust and more holistic understanding of the present and future risks of climate warming to freshwater biodiversity and ecosystems across Japanese river networks, contextual to their specific present and future climatological, biological, and environmental conditions. In particular, we focused on the following research questions: (1) what are the main environmental factors controlling stream water temperatures and how will these temperatures change across Japanese river networks under future climate change? (2) how will these changes impact freshwater species, their habitats, and ecosystems? (3) how will current biodiversity patterns be modified, and what will be the ecosystem implications?

３．研究の方法

To answer these research questions, the project involved a combination of different complementary research methods including:

(1) Field monitoring. The establishment of temperature monitoring networks comprising hundreds of sites across four river catchments, representative of different geographical areas in Japan (the Sorachi and Teshio Rivers in Hokkaido, The Kiso River in Honshu, and the Hiji River in Shikoku; Fig.1), were established to measure paired air/water temperatures over the duration of the project. The sites were selected to cover as much as possible the full range of environmental gradients (e.g., land use, riparian cover, slope, stream order). Biological assessment (fish and macroinvertebrates) was also conducted at the monitoring sites.

(2) Statistical models (generalized linear models) were used to predict water temperatures as a function of air temperature and environmental covariates known to be important in controlling water temperature dynamics in streams. These models were then used to assess the relative importance of environmental controls on water temperatures in the study catchments. Statistical analyses were also conducted to evaluate the effect of different stream thermal conditions on the distribution patterns of species and community composition.

(3) In combination with future air temperatures based on regional climate projections under alternative emission scenarios, use the temperature models to analyze the potential impacts of changes in instream habitat conditions for representative freshwater species.

(4) Use of outdoor experiments to disentangle the effects of warming and heatwaves, mimicking future conditions projected for our study region, on freshwater species, community composition, and ecosystem functions.

4．研究成果

Using paired air–water mean daily, monthly, and seasonal summer temperatures collected over four years from hundreds of monitoring stations within our four study catchments (Fig. 1), we first investigated the role of different climatic (air surface temperature and precipitation) and environmental parameters in controlling stream water temperatures. We found that a range of environmental drivers operating at different spatial scales, from catchment (e.g., proportion of geological formation and land use within the contributing catchment) to stream reach (e.g., riparian cover and elevation), had strong effects on stream water temperatures. However, the magnitude of these effects was found to depend on the temporal scale of the analysis (Fig. 2a) [7]. Whereas drivers operating at local (reach) scales, like riparian cover, had a strong significant effect and relative importance over daily water temperatures, this dominance was reversed by drivers operating at larger (catchment) scales, like the proportion of volcanic geology or land use, for monthly temperatures. These results highlight the importance of contextualizing the effects of environmental controls on water temperatures to the timescale of the analysis particularly when informing management and conservation decisions. Further analyses revealed the crucial role of volcanic geology, as a proxy for cold groundwater inputs, in regulating stream summer water temperatures. Volcanic spring-fed streams were found to have up to 3.3 °C lower mean summer temperatures than non-volcanic streams (Fig. 2b), an effect that was more pronounced in streams with less summer precipitation or lower air temperatures [8].

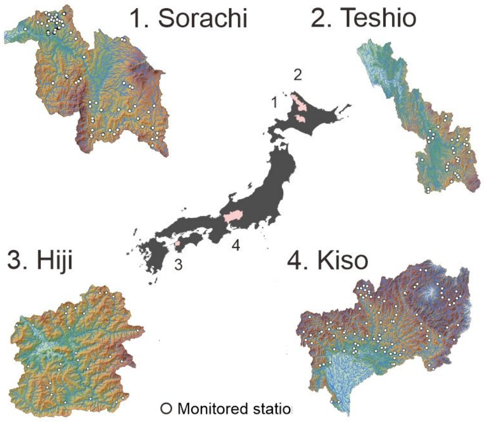

Figure 1. Location of the four study catchments and the paired air/water monitoring stations.

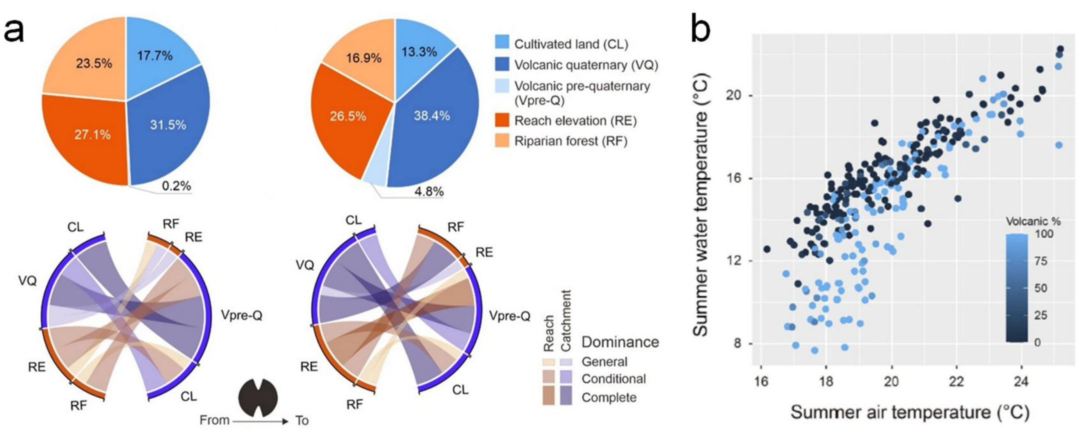

Figure 2. (a) Relative importance (top row) and pair-wise dominance (bottom row) analysis of different catchment- and reach-scale environmental covariates on daily (left column) and monthly (right column) summer stream water temperatures (source García Molinos et al. 2022). Dominance is established from the left side predictors towards the right-side predictors in the diagrams; the width and colour of the link indicating the strength of the dominance. (b) Relationship of the mean summer air temperature and watershed geology, namely the proportion of volcanic rock in the watershed, to the mean summer water temperature (source Ishiyama et al. 2023).

Volcanic spring-fed streams were found to act as cold habitat refugia with distinctive associated communities of invertebrate and fish species comprising a larger number and greater abundance of cold-water species than those from nearby non-volcanic streams [8]. Wider access to these cold refugia across the river network is also very important to support basin-scale distribution of riverine fish. Using environmental DNA and its relationship with water temperature, we look at the spatiotemporal distribution of the ayu (*Plecoglossus altivelis*) from summer growth to autumn spawning periods in the Nagara River basin, one of the main tributaries of the Kiso River [9]. We found that the species distribution across the river network was intimately related to seasonal water temperature patterns. During the warmest period of the summer (August), individuals concentrated in different sections of the river network with relatively cool water (< 25 °C), such as the upper mainstem, or in specific tributaries and downstream their confluences with the mainstem. Conversely, during early autumn, without the constraint of high-water temperatures, individuals spread widely in the middle and upper mainstem and gradually aggregated into the middle mainstem during late autumn for the downstream spawning migration as water temperatures decreased below 20 °C. This demonstrates the importance of maintaining connectivity within the river network and access to cold water refugia used by aquatic species, including culturally and commercially important species like the ayu, during different stages of their life cycle.

The importance of these volcanic springs as future climate refugia was also demonstrated by our model projections where we assessed the capacity of different types of streams to retain their suitable habitat conditions for cold-water species in the by mid (2050s) and late (2070s) century under alternative emission scenarios using our statistical water temperature models [8]. Our results revealed a geology-related pattern of thermal habitat loss for cold-water species. Whereas nonvolcanic streams were projected to rapidly decline in thermally suitable habitats for two cold-water sculpins (*Cottus nozawae* and *Cottus pollux*), even under the lowest emission scenario (RCP 2.6), most volcanic streams retained their cold-water habitats below the species' thermal thresholds. However, this effect was contingent to the prevailing climatic conditions. In regions with high summer precipitation, where surface runoff represents a large contribution to the streams, less than 25% of the 140 sites used in this study were found to remain thermally suitable for the species even under the lowest emission scenario regardless of their geological make-up (RCP2.6). These results highlight the potential for volcanic streams to act as climate refugia under future climate change and stress the importance for jointly considering underlying geology and climatic conditions for their effective identification and management.

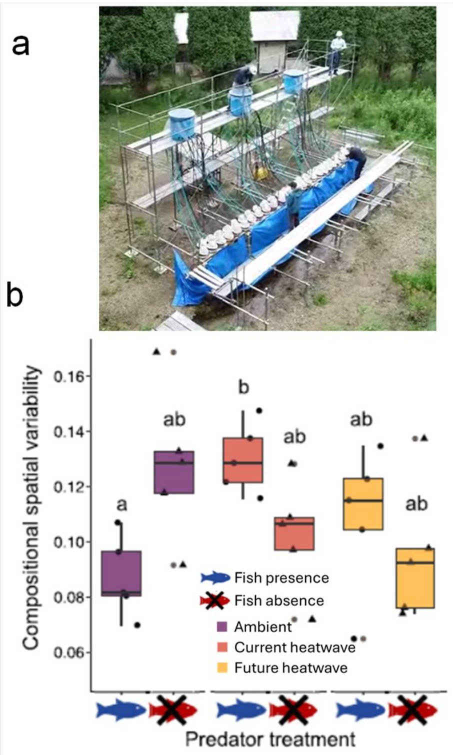

Figure 3. (a) Aerial view of the experimental system. (b) Box plots comparing compositional spatial variability of algal communities in the experimental mesocosms at the peak of the heatwave application for each treatment combination (reproduced from Ross et al. 2021). The experiment was conducted in Hokkaido University Tomakomai Experimental Forest in collaboration with researchers from Trinity College, University of Dublin (Ireland).

To explore the potential effects of climate change-driven species redistributions and extinctions on the impacts of climate change on biodiversity and ecosystem functioning, we conducted an outdoor mesocosm experiment where we exposed benthic communities (algae and invertebrates) to heatwaves with or without the presence of sculpin (*Cottus nozawae*), a locally abundant cold-water predatory fish species (Fig. 3a) [10]. Heatwaves were recreated to mimic local conditions in the study area according to observed (1995-2017 series from Tomakomai weather station) and projected (2076-2096 from 5-km resolution dynamical downscaled model NHRCM05 for a high-emission scenario RCP8.5) daily temperatures. Benthic algae biomass and composition, invertebrate density and richness, and leaf litter decomposition rates were measured as response variables during and after the application of heatwaves to measure the impacts of, and recovery from, heatwaves. Our results showed that heatwaves destabilized algal communities by homogenizing (simplifying) them in space but only when the fish predator was absent (Fig. 3b). Interestingly, other heatwave impacts on benthic algae and macroinvertebrate (e.g., compositional changes or biomass) only emerged during the recovery period after the application of the heatwaves. These results suggest that legacy effects from heatwaves can amplify over time as they propagate through biological interaction networks, but the presence of predators can help to buffer such impacts. This stresses the importance of conserving trophic structure and highlights the potential for species extinctions to amplify the effects of climate change and extreme events. Importantly, we found that several heatwave effects, particularly on algal biomass and macroinvertebrate community structure, were weaker or non-detectable under current but not future heatwaves. This result underscores the importance of avoiding extreme warming scenarios by enforcing strict climate change mitigation policies. Further experiments conducted in collaboration with international partners showed that the effects of future warming and heat waves can also interact with other existing stressors (such as nutrient enrichment or herbicides) in freshwater systems to disrupt the performance, phenology, and trophic interactions of organisms, such as macrophytes and freshwater plankton, in complex and unexpected ways [11-13].

Altogether, our results represent a novel and compelling evidence, generated through a variety of approaches and methods, demonstrating the complex nature of climate change impacts to freshwater biodiversity and ecosystems in Japan and worldwide. Our work stresses the need to consider these impacts in the wider context of other environmental drivers governing water temperature dynamics in streams (chiefly geology), as well as their interaction with other factors (e.g., biotic interactions) and existing stressors (e.g., water pollution and nutrient enrichment) that can ultimately magnify or reduce the effects of climate warming acting in isolation. Finally, our work highlights the importance of implementing measures to properly identify and protect cold water habitats in river networks, such as those provided by volcanic spring-fed streams, to conserve biodiversity and act as climate refugia against future climate changes.

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５．主な発表論文等

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２．論文標題 Synergistic effects of warming and eutrophication alert zooplankton predator-prey interactions along the benthic-pelagic interface	５．発行年 2021年
３．雑誌名 Global Change Biology	６．最初と最後の頁 5907～5919
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オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Fu Hong、Gauzere Pierre、Garcia Molinos Jorge、Zhang Peiyu、Zhang Huan、Zhang Min、Niu Yuan、Yu Hui、Brown Lee E.、Xu Jun	４．巻 204
２．論文標題 Mitigation of urbanization effects on aquatic ecosystems by synchronous ecological restoration	５．発行年 2021年
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２．論文標題 Effects of warming, climate extremes and phosphorus enrichment on the growth, sexual reproduction and propagule carbon and nitrogen stoichiometry of Potamogeton crispus L	５．発行年 2020年
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２．論文標題 VoCC: An R package for calculating the velocity of climate change and related climatic metrics	５．発行年 2019年
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１．著者名 Fu Hong、Xu Jun、Zhang Huan、Garcia Molinos Jorge、Zhang Min、Klaar Megan、Brown Lee E.	４．巻 316
２．論文標題 A meta-analysis of environmental responses to freshwater ecosystem restoration in China (1987-2018)	５．発行年 2023年
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２．論文標題 Macroinvertebrate and environmental responses to dredging and submerged macrophytes transplantation	５．発行年 2024年
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２．論文標題 Interactions between climate warming, herbicides, and eutrophication in the aquatic food web	５．発行年 2023年
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2．論文標題 Geology‐climate interactions are key determinants of climate‐change refugia in Japanese mountain streams	5．発行年 2023年
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2．論文標題 Underlying geology and climate interactively shape climate change refugia in mountain streams	5．発行年 2023年
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掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
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1．著者名 石山信雄	4．巻 74
2．論文標題 流域地質と気候が作り出すClimate-change refugia：気候変動下での河川ネットワーク管理におけるその重要性	5．発行年 2023年
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オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

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〔図書〕　計0件

〔産業財産権〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究分担者	石山　信雄 (Ishiyama Nobuo) (50780821)	地方独立行政法人北海道立総合研究機構・森林研究本部　林業試験場・主査 (80122)	
研究分担者	末吉　正尚 (Sueyoshi Masanao) (70792927)	国立研究開発法人国立環境研究所・生物多様性領域・研究員 (82101)	

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究協力者	中村　太 (Nakamura Futoshi)		

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関