

実験数理研究分野

客員教授 山岡 雅直 (2016年6月～現在)

助 教 JUSUP Marko (2016.3～2018.3)

*2018～、東京工業大学、特任助教

1. 研究目標

(1) 実験数理研究分野では、これまでのコンピュータの性能向上を担ってきた半導体の微細化が終焉を迎え、コンピュータの性能が向上しなくなる近い将来に向けて、新しい動作概念を用いたコンピューティング手法の開発をめざす。特に、自然現象の創発現象を用いた新概念コンピューティングを題材にし、これまでのコンピューティング手法では実現できなかった計算価値を生み出すことをめざす。

新概念コンピューティングの実用化に向けては、社会課題から実際にコンピューティング技術を適用するアプリケーションを抽出し、自然現象にマッピングする数理モデル化の技術が必要となる。今回、この自然現象として、磁性体の振る舞いを表すイジングモデルを用いることで、組合せ最適化問題が解けるということに着目し、イジングモデルを用いた計算機を検討している。このイジングモデルを用いた数理モデル化により、イジングモデルにマッピングされた結果は通常は社会一般の形をとるため複雑なネットワーク構造をとっている。一方で、現在の実装技術を考えてと新しい概念のイジング計算機を実現するハードウェアでは、大規模化や高性能化に向けて規則的なネットワーク構造しか表現できず、そこにモデル化した結果との乖離が生まれる。そこで、社会の複雑なネットワーク構造から規則的なグラフへの課題を埋め込みことによって、複雑な社会問題を新しいコンピューティング技術で解くことが可能となる。よって、本研究分野では、このネットワーク構造を埋め込むためのグラフ埋め込み技術の開発を行う。

さらに、新しい概念のコンピューティング技術では、そのコンピューティング原理自体が数理学の原理に基づいており、この性能を向上させるためには数理科学的な解析が必要となる。たとえば、自然現象の収束動作を用いたコンピューティング技術では、その収束動作をどのようにしてコンピュータ上に再現するかは大きくコンピュータの性能に影響する。この収束動作を数理的な理論に基づいて解析し、それを実際のハードウェア上に再現することが必要となる。本研究分野では、こういった数理化学に基づいたコンピューティングの動作原理の改善もめざす。

このように、本研究分野では、数理学を用いて、実社会に役立つ情報科学の技術確立することをめざす。

2017年度は、イジング計算機の性能向上及び実応用の開発をめざし、それぞれのターゲットにとって必要な連携先と議論することで、これらの課題を達成する。より特定のには、アプリケーションレイヤに関しては、機械学習分野の知見が必要となるため、情報科学分野との連携により、

イジング計算機へのブースティング技術の適用をめざす。ソフトウェアレイヤおよび計算機レイヤに関しては、数理科学の知見が必要となるため、数理科学分野との連携によりグラフ埋め込み技術の開発とイジングモデルのエネルギーランドスケープの解析技術の開発を行う。

(2) 統合的でグローバルな視点に立った研究は、社会にとって実用上重要な問題に取り組む可能性を秘めている。この研究で取り組む具体的な問題は、生態学から生物学、社会学、さらには経済学に至るまで非常に多様な起源を持つかもしれないが、数学の普遍的言語に翻訳されると、これらの問題の根底にある原則やプロセス等は同様の形になる。この形を認識し、対応する動的性質を理解することは、RIES で国内外の共同研究者と共に行われた分析の中核である。

この研究の最も重要な目的は、複雑な生態学的、生物学的、社会的、経済学的現象の数学的モデルを定式化し、これらの問題の動的性質を分析することである。また、社会にとって実用的な意味を持つ解決策を見つけることが目的である。

こういう目的を果たすため、3つの主要な目的に焦点を当てた：

- ・エネルギー計上のアプローチを使って、生物が環境変化にどのように反応するかというのを明らかにすること。
- ・社会的ジレンマに直面した時の人間行動をよりよく理解すること。
- ・環境状況に応じて生物資源の動態、又これに対する人間行動を予測すること。

2. 研究成果

(1) アプリケーションレイヤでは、情報科学研究科や保健科学研究所との連携体制を構築し、機械学習応用や農事計測データへの応用に関する研究を進めた。特に、機械学習応用につながる技術として、グラフ埋め込み技術(図1)にフォーカスした、産学連携初となる北大・日立プログラミングコンテストを開催した。

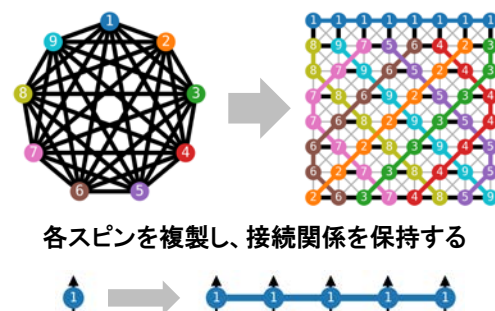


図1：グラフ埋め込み技術。アプリケーションとつながる元の問題の複雑なグラフ構造をハードウェア上の規則的なグラフ構造に置き換える技術。元の問題の一つのスピンをハードウェア上の複数のスピンで表現することで、接続関係を保持し、問題を置き換えることが可能。

このプログラミングコンテストは、2017/11～12月にWeb上で行われた。コンテスト上では、参加者が解答をWeb上にアップデートするとその場で採点が行われ、順位が変動して通知されるという形をとった。そのための、採点の基準や仕組みなどを情報科学研究科と連携して作り上げ、実際にコンテスト上でリアルタイムに採点を行うことを可能とした。コンテストは、グラフ埋め込みに関連する課題2問をそれぞれ2週間ずつかけて解く形として実施した。1問目は、最適化問題の近似解を得る際に使える埋め込み技術として一部の接続情報が失われても効率的に埋め込むことの技術に関する問題、2問目は最適解の正確な解が必要な場合に使える技術としてすべての接続情報を維持し弾m効率的に埋め込む技術に関する問題を設定した。1問目は、973名が登録し、296名が解答を提出した。2問目は、問題自体が多少難しかったこともあり、446名が登録し、126名が解答と提出した。当初想定した以上の性能の解答が集まり、非常にレベルの高いコンテストとなり、そこで得られたコードにより、実際に埋め込む効率が高くなり、100スピン以上埋め込める規模が拡大することを確認した(図2)。

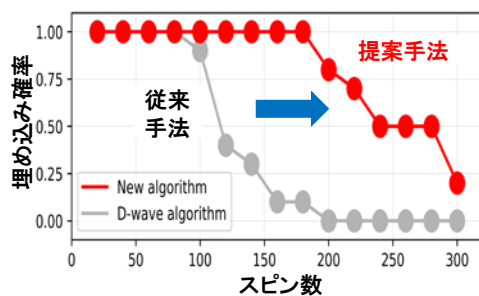


図2: プログラムコンテストの優勝コードを用いた場合の効果。100%のスピンを埋め込むが必要となるが、従来手法と比較して100スピン以上効率が向上して埋め込めるスピン数が2.3倍程度に向上していることが確認できる。これは、さらに大規模な問題ではさらに埋め込めるスピン数が増大することを示している。

さらに上記のグラフ埋め込み技術を用いて、機械学習の一種であるブースティング技術への応用技術の開発を行った。これは、Qboostと呼ばれているアルゴリズムで、弱分類器と呼ばれる識別器を複数組み合わせることで強分類器を構成する技術である。機械学習では、学習によりこの強分類器の精度を向上させ、学習による分類性能k字を向上させる技術である。ここに、上記のグラフ埋め込み技術、特にプログラムコンテストの問題1で出てきた技術を使う場合には、一部情報が劣化してしまうためその部分を補償する必要がある。そこを、イジングモデルの外部磁場係数に補償パラメータを付加することで補償するアルゴリズムを提案し、FPGAに実装した。それにより、従来のCPUで計算した場合には約4時間かかる計算を、FPGA上で5秒で実行できることを確認し、またQboostでの繁華性能が劣化しないこと

を確認した。

(2) この研究では複数の結果が得られた。下記各結果について簡単な説明が含まれている。

・ We examined whether two widely known cooperation-promoting mechanisms—network reciprocity and costly punishment—create synergies in social dilemma experiments. While network reciprocity fulfilled its expected role, costly punishment proved to be surprisingly ineffective in promoting cooperation. This ineffectiveness suggests that the rational response to punishment assumed in theoretical studies is overly stylized and needs reexamining.

1) Li X-L, Jusup M, Wang Z, Li H-J, Shi L, Podobnik B, Stanley HE, Havlin S, Boccaletti S (2018) Punishment diminishes the benefits of network reciprocity in social dilemma experiments. Proc Natl Acad Sci USA 115: 30-35.

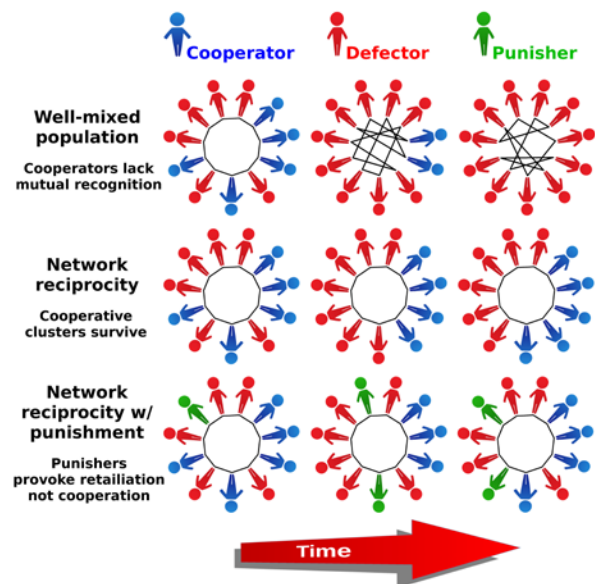


図3 How cooperation develops due to network reciprocity and how punishment fails to improve overall cooperativeness.

・ Cyprinid fishes are often hypothesized to be less sensitive to chemical stress than comparable fish families, yet few empirical tests of this hypothesis exist. We developed a statistical model in which the no-effect concentrations (NECs) of 29 fish species from 13 families exposed to an acetylcholinesterase inhibitor pesticide (carbaryl, chlorpyrifos, or malathion) were used as the response variable. Our results indicate that the NECs for cyprinid fishes were significantly higher than those for other fishes, suggesting that cyprinids are indeed less sensitive to the three studied pesticides.

1) Iwasaki Y, Jusup M, Shibata K, Nagai T, Kashiwada S (2018) Lower sensitivity of cyprinid fishes to three acetylcholinesterase inhibitor pesticides: an evaluation based on no effect concentrations. Limnology 19: 1-5.

- Living complex systems create functionalities by pairing up complementary processes, one to build and another to correct and clean the space for more building. When these processes are embedded into mutually exclusive phases, establishing a balance between them requires a phase flipping mechanism. We demonstrated that when a neuronal network flipping between excited and resting phases gives rise to a statistical conservation law of synaptic strength. Furthermore, this law is selected by evolution regardless of the network's initial state, thus reconciling biology with the physical concept of self-organized criticality.

1) Podobnik B, [Jusup M](#), Tiganj Z, Wang W-X, Buldú JM, Stanley HE (2017) Biological conservation law as an emerging functionality in dynamical neuronal networks. *Proc Natl Acad Sci USA* 114: 11826-11831.

- Understanding the relationship between the environmental conditions and life-history traits, such as growth, reproduction, and size at specific life stages, is important for understanding the population dynamics of a species and for constructing adaptable, relevant, and efficient conservation measures. Using a mechanistic modeling approach adapted to an endangered species of marine turtles (the loggerhead turtle), we found that the ultimate size (length and mass) is primarily affected by food availability, whereas growth and maturation are primarily affected by temperature whilst also showing positive correlation with available food. Reproduction increases with both food availability and temperature because food availability determines energy investment into egg production, and temperature affects the rate of related processes (such as vitellogenesis).

1) Marn N, [Jusup M](#), Legovic T, Kooijman SALM, Klanjscek T (2017) Environmental effects on the life-history and metabolism of loggerhead turtles. *Ecol Model* 360: 163-178.

- Among the central tenets of globalization is the free migration of labor, but little is known about how antiglobalist sentiment can be affected by high levels of immigration. We analyzed poll data from EU countries at the center of the recent migrant crisis, and found that in the period from 2015–2017 the percentage of right-wing (RW) populist voters in any given country depends on the prevalence of immigrants in this country's population and the total immigration inflow into the EU as a whole. The latter phenomenon is likely caused by the EU's organization as a supranational state—lacking inner borders means that “someone else's problem” easily become “my problem.” Furthermore, the increase in the percentage of RW voters considerably exceeds the percentage of immigration inflow. Therefore, if the fast immigration process continues, ongoing democratic processes will cause RW populism to prevail and globalization to rapidly decrease. We locate tipping points between the fraction of immigrants and the rise of RW populism.

1) Podobnik B, Jusup M, Stanley HE (2017) Predicting the rise of EU

right-wing populism in response to unbalanced immigration. *Complexity* 2017: 1580526.

- Overuse of common-pool resource often occurs due to the rational act from the perspective of one's own self-interest. Although punishing those harvesters who overuse the resource may seem as a straightforward solution, a number of practical problems arise. For example, if harvester delegate the enforcement to a specialised entity (consisting of e.g. police officers, inspectors, rangers etc.), curbing corruption becomes a major challenge. We extended an existing simplistic evolutionary game model of corruption by combining it with the resource dynamics to establish a more general and powerful analytical framework. In this framework, in addition to the usual socio-economic incentives, ecological parameters also affect the prospects of reaching a cooperative outcome. We find, for example, that the more resilient the resource (as implied by a high growth rate), the more likely the dominance of corruption. This result indicates that illegal logging and fishing observed in productive terrestrial and marine ecosystems, respectively, are encouraged by the ecological characteristics of these systems. Although one might expect that in productive ecosystems, a high resource growth rate should dramatically improve the profits of harvesters who cooperate, a deeper level of analysis reveals that the incentive for overusing the resource arises from the increasing opportunity cost incurred by cooperators who sustainably restrain their efforts.

1) Lee J-H, [Jusup M](#), Iwasa Y (2017) Games of corruption in preventing the overuse of common-pool resources. *J Theor Biol* 428: 76-86.

- Social-dilemma and other socio-economic experiments often require full anonymity to avoid the effects of multiple compounding factors. However, the main mechanisms for the evolution of cooperation share one common characteristic—reduced anonymity relative to a primitive, well-mixed population. Accordingly, we conducted a social dilemma experiment to test whether onymity bolsters cooperation in a repeated Prisoner's dilemma game with anonymous and onymous pairwise encounters. We found that the frequency of cooperation and the median payoff per round increase significantly under onymity relative to anonymity. More importantly, the correlation between players' rank and the use of strategies (cooperation, defection, or punishment) undergoes a significant change, rewarding onymous prosocial actions with a higher ranking. The main conclusion is that prosocial behavior under onymity pays back or, in layman's terms, that winners play nice.

1) Wang Z, [Jusup M](#), Wang R-W, Shi L, Iwasa Y, Moreno Y, Kurths, J (2017) Onymity promotes cooperation in social dilemma experiments. *Sci Adv* 3: e1601444.

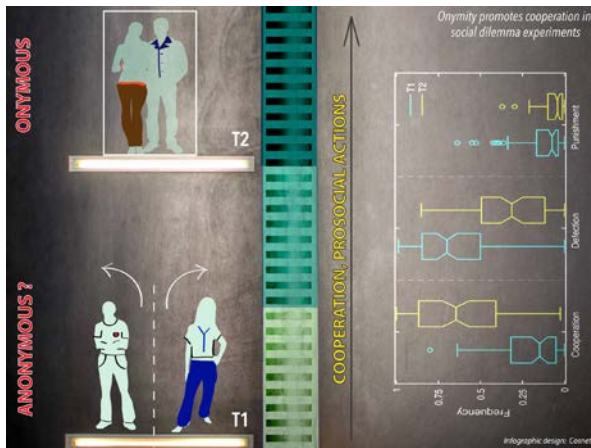


Fig. 4 Onymous situation promotes cooperation relative to an anonymous one although there are no purely rational reasons for this.

- Loggerhead turtle is an endangered sea turtle species with a migratory lifestyle and worldwide distribution, experiencing markedly different habitats throughout its lifetime. We provide new information on biology and ecology of this species by: (i) Synthesizing existing information on loggerhead turtles and assimilating several decades worth of jointed data sets into a full life cycle model built on the principles of a general metabolic theory. (ii) Exploring the physiological energetics of the loggerhead turtle in terms of hard-to-obtain indicators such as the time to reserve depletion under starvation or an energy budget encompassing all phases of ontogeny. Furthermore, we utilized a unifying methodology which is immediately applicable to other sea turtles and, in fact, organisms of other marine species, thus setting the stage for future extensive studies in comparative physiological energetics.

1) Marn N, Kooijman SALM, Jusup M, Legovic T, Klanjscek T (2017) Inferring physiological energetics of loggerhead turtle (*Caretta caretta*) from existing data using a general metabolic theory. *Mar Environ Res* 126: 14-25.

- The abundance of young Atlantic bluefin tuna tripled in the northwestern Mediterranean following effective management measures in recent years. This raised a question: Has predation of bluefin tuna on sardine and anchovy been responsible for biomass decline of these small pelagic fish species? A multifactor analysis combining: (i) the observed diet composition of bluefin tuna, (ii) their modelled daily energy requirements, (iii) their population size, and (iv) the abundance of prey species in the area collectively yielded the proportion of the prey populations that were consumed by bluefin tuna annually between 2011-2013. We estimated that the annual consumption of small pelagic fish by bluefin tuna is less than 2% of the abundance of these populations. Tuna predation, therefore, is unlikely to be the main cause of major changes in the small pelagic fish populations from northwestern Mediterranean.

1) Van Beveren E, Fromentin J-M, Bonhommeau S, Nieblas A-E, Metral L, Brisset B, Jusup M, Bauer RK, Brosset P, Saraux C (2017) Prey predator interactions in the face of effective management strategies: changes in Mediterranean small pelagics are not due to increased tuna predation. *Can J Fish Aquat Sci* 74: 1422-1430.

- Immigration issues, in addition to being an often polarizing social topic, represent an interesting problem of non-equilibrium thermodynamics. If the immigration inflow is out of balance with the integration rate of a society, potentially dangerous conflicts may arise. We modeled how the social fabric—described by combining the elements of evolutionary games and complex networks—responds to different immigration scenarios. Subsequently, we isolated those scenarios that may disrupt the normal functioning of the society and identified the characteristics of successful immigration policies. In particular, these characteristics require that: (i) the tolerance of insiders is in balance with the assimilation of outsiders, (ii) the tolerant insiders maintain a sustainable majority, and (iii) any reduction in benevolence of the majority occurs smoothly.

1) Podobnik B, Jusup M, Wang Z, Stanley HE (2017) How fear of future outcomes affects social dynamics. *J Stat Phys* 167: 1007-1019.

- We reviewed Dynamic Energy Budget (DEB) theory—likely the most potent macroscopic unifying theory in biology today. The theory, with a special focus on fundamental laws of physics, unifies processes on multiple scales of biological organization into a single modeling framework: (i) nano- and micro-scale level by utilizing concepts in molecular biology (molecular transport and transformation, enzyme kinetics, and regulation) to arrive at functionals describing state variables necessary for organism function; (ii) sub-organismal level by capturing fluxes of material and energy within functional compartments; (iii) organismal-level by describing growth, reproduction, and aging of organisms as determined by the environmental conditions experienced by the organism; (iv) population-level through creation of DEB-based population models; and even (v) ecosystem-level by capturing feedbacks between the environment and the population. Our review offers considerable advantages over previous ones: focus on fundamental laws of physics rather than just operational descriptions of the work; step-by-step derivation of the fundamentals and the standard DEB model; and demonstrations of how DEB has already been used in achieving points (i)–(v) above. These demonstrations are crucial for bridging the gap between often disjointed disciplines of physics and life sciences: while the theoretical introduction will appeal to the former, the examples will bring home the message to the latter.

1) Jusup M, Sousa T, Domingos T, Labinac V, Marn N, Wang Z, Klanjscek T (2017) Physics of metabolic organization. *Phys Life Rev* 20: 1-39.

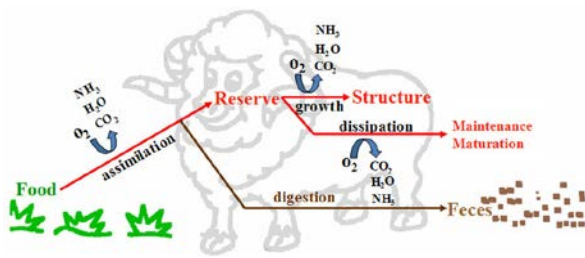


図5 All heterotrophic aerobes perform three types of macroscopic transformations: assimilation, growth, and dissipation. Oxygen is consumed in the process, while inorganic metabolites (ammonia, water, and carbon dioxide) are excreted into the environment. Feces is a result of the digestive system's inefficiencies.

・ Infectious diseases are a threat to human health and a hindrance to societal development. Consequently, the spread of diseases in both time and space has been widely studied, revealing the different types of spatial patterns. Transitions between patterns are an emergent property in spatial epidemics that can serve as a potential trend indicator of disease spread. Despite the usefulness of such an indicator, attempts to systematize the topic of pattern transitions have been rare. We reviewed pattern transitions in spatial epidemiology, describing the types of transitions and their underlying mechanisms. We showed that pattern transitions relate to the complexity of spatial epidemics by, for example, being accompanied with phenomena such as coherence resonance and cyclic evolution. The reviewed results provide new insights into disease prevention and control, and may even be applicable outside epidemiology, including other branches of medical science, ecology, quantitative finance, and elsewhere.

1) Sun G-Q, Jusup M, Jin Z, Wang Y, Wang Z (2016) Pattern transitions in spatial epidemics: Mechanisms and emergent properties. *Phys Life Rev* 19: 43-73.

・ A large proportion of human malaria infections is asymptomatic, yet serves as a reservoir that sustains malaria transmission. To achieve malaria elimination, it is important to understand how the asymptomatic infections affect malaria transmission among humans. We proposed a simple mathematical model of malaria transmission with both symptomatic and asymptomatic malaria infections, and investigated an effect of interventions targeting the reservoir population during an early phase of malaria spread under different transmission settings.

1) Funo T, Inaba H, Jusup M, Tsuzuki A, Minakawa N, Iwami S (2016) Impact of asymptomatic infections on the early spread of malaria. *Jpn J Ind Appl Math* 33: 671-681.

・ In the case of an epidemic, a better immunization strategy can save comparatively more lives and still observe the constraints of a limited budget. Because human lives are at stake, the subject of efficient immunization has received considerable attention among network scientist, resulting in the strategies based

on such statistical properties as degree centrality (the number of neighbors a node has) or betweenness centrality (the number of shortest paths between any two nodes in a network on which a given node lies). Recognizing the need for efficient and practical immunization, we drew inspiration from an amoeboid organism capable of performing complex computational tasks to devise a strategy that considers both the number of neighbors a node has and the way the neighbors are linked among themselves. The resulting immunization strategy performs at least as good as its strongest competitor, but usually considerably better (2 to 20 times). Ours is, therefore, an important contribution to immunization science of immediate interest to medical scientists, as well as public health officials looking for methods to control epidemics.

1) Liu Y, Deng Y, Jusup M, Wang Z (2016) A biologically inspired immunization strategy for network epidemiology. *J Theor Biol* 400: 92-102.

3. 今後の研究の展望

(1) 2017年度は、グラフ埋め込み技術を開発し、そのブースティングへの応用実験を行ったが、この技術をさらに発展させ、ブースティング向け高速最適化処理技術(1sec/回)と汎化性能向上(1%以下)のための最適学習アルゴリズムと定式化手法を導出する。これは、数学および情報分野連携により実施する。

また、イジング計算機のさらなる高性能化に向けて、イジング計算機のスピン同時更新を可能にする確率セルオートマタアルゴリズムを発展させて活用し、数学的精度補償に基づく高速基底状態探索手法を構築する。これにより、イジング計算機の収束時間の短縮が可能となり、飛躍的な計算機性能向上が期待できる。さらにこの手法をイジング計算機のFPGAプロトにより原理実証を行う。

また、プログラムコンテストで得られたグラフ埋め込み技術は、さらなる高性能化が期待できるため、その結果を基にした高精度埋め込みアルゴリズム(埋め込みスピン数2倍改善)の開発を行う。この結果に関しても、イジング計算機のFPGAプロトタイプに適用し、効果の実証を行う。

また、さらなる適用先の拡大に向けて、量子化学分野に分子エネルギー計算等、自然科学へのイジング計算機の適用をターゲットとした研究体制の構築と将来に向けた新たなハードアーキテクチャの導出を行う。

(2) 今後の研究は、これまでに様々な研究の観点から得られた結果・知識を統一すべきだ。例えば、生物資源の持続的な利用のためには、変化する環境に応じてこの生物資源の動態も、持続的な利用政策に対する人間の協力も、両方をより深く理解する必要がある。特に、現代社会の緊急問題を解決するためには、人間の協力が不可欠である。例えば、気候変動の悪影響を避けるためには、大規模な国際協

力が必要である。又、公衆衛生の観点からは、集団免疫を維持するには、ワクチン接種プログラムとの広範な協力が必要である。

上記問題の解決に貢献するために、本研究では様々な場面における人間協力を促進する要因を実験的に調べる。実験結果を用いて、進化ゲーム理論のフレームワークを参考し、人間行動の新しい数理モデルを作り出す。さらに、こういう風に作り出した数理モデルを例え、生物資源動態の数理モデル又は、流行病の数理モデルと合わせて、効果的な政府政策を推薦できるように努力する。

4. 資料

4.1 学術論文（査読あり）

- 1) Li X-L, [Jusup M](#), Wang Z, Li H-J, Shi L, Podobnik B, Stanley HE, Havlin S, Boccaletti S (2018) Punishment diminishes the benefits of network reciprocity in social dilemma experiments. *Proc Natl Acad Sci USA* 115: 30–35. [Equal contribution; Corresponding author]
- 2) Iwasaki Y, [Jusup M](#), Shibata K, Nagai T, Kashiwada S (2018) Lower sensitivity of cyprinid fishes to three acetylcholinesterase inhibitor pesticides: an evaluation based on no effect concentrations. *Limnology* 19: 1–5.
- 3) Podobnik B, [Jusup M](#), Tiganj Z, Wang W-X, Buldú JM, Stanley HE (2017) Biological conservation law as an emerging functionality in dynamical neuronal networks. *Proc Natl Acad Sci USA* 114: 11826–11831.
- 4) Marn N, [Jusup M](#), Legovic T, Kooijman SALM, Klanjscek T (2017) Environmental effects on the life-history and metabolism of loggerhead turtles. *Ecol Model* 360: 163–178.
- 5) Podobnik B, Jusup M, Stanley HE (2017) Predicting the rise of EU right-wing populism in response to unbalanced immigration. *Complexity* 2017: 1580526.
- 6) Lee J-H, [Jusup M](#), Iwasa Y (2017) Games of corruption in preventing the overuse of common-pool resources. *J Theor Biol* 428: 76–86.
- 7) Wang Z, [Jusup M](#), Wang R-W, Shi L, Iwasa Y, Moreno Y, Kurths, J (2017) Onymity promotes cooperation in social dilemma experiments. *Sci Adv* 3: e1601444. [Corresponding author]
- 8) [Jusup M](#), Sousa T, Domingos T, Labinac V, Marn N, Wang Z, Klanjscek T (2017) The universality and the future prospects of physiological energetics: Reply to comments on “Physics of metabolic organization”. *Phys Life Rev* 20: 78–84.
- 9) Marn N, Kooijman SALM, [Jusup M](#), Legovic T, Klanjscek T (2017) Inferring physiological energetics of loggerhead turtle (*Caretta caretta*) from existing data using a general metabolic theory. *Mar Environ Res* 126: 14–25.

[Corresponding author]

- 10) Van Beveren E, Fromentin J-M, Bonhommeau S, Nieblas A-E, Metral L, Brisset B, [Jusup M](#), Bauer RK, Brosset P, Saraux C (2017) Prey predator interactions in the face of effective management strategies: changes in Mediterranean small pelagics are not due to increased tuna predation. *Can J Fish Aquat Sci* 74: 1422–1430.
- 11) Podobnik B, [Jusup M](#), Wang Z, Stanley HE (2017) How fear of future outcomes affects social dynamics. *J Stat Phys* 167: 1007–1019.
- 12) [Jusup M](#), Sousa T, Domingos T, Labinac V, Marn N, Wang Z, Klanjscek T (2017) Physics of metabolic organization. *Phys Life Rev* 20: 1–39.
- 13) Sun G-Q, [Jusup M](#), Jin Z, Wang Y, Wang Z (2016) Disease control framework based on spatial epidemiology: Reply to comments on “Pattern transitions in spatial epidemics: Mechanisms and emergent properties”. *Phys Life Rev* 19: 103–106.
- 14) Sun G-Q, [Jusup M](#), Jin Z, Wang Y, Wang Z (2016) Pattern transitions in spatial epidemics: Mechanisms and emergent properties. *Phys Life Rev* 19: 43–73. [Corresponding author]
- 15) Funo T, Inaba H, [Jusup M](#), Tsuzuki A, Minakawa N, Iwami S (2016) Impact of asymptomatic infections on the early spread of malaria. *Jpn J Ind Appl Math* 33: 671–681.
- 16) Liu Y, Deng Y, [Jusup M](#), Wang Z (2016) A biologically inspired immunization strategy for network epidemiology. *J Theor Biol* 400: 92–102. [Corresponding author]

4.2 学術論文（査読なし）

該当なし。

4.3 総説・解説・評論等

該当なし。

4.4 著書

該当なし。

4.5 講演

a. 招待講演（国際学会）

- 1) Jusup M with Tsuzuki A, Funo T, Inaba H, Morioka Y, Doi T, Behera S, Hashizume M, Kruger P, Minakawa N, Iwami S: Wavelet analysis implies a link between climate phenomena and malaria incidence in South Africa. 64th Annual Meeting of Ecological Society of Japan, Tokyo, Japan, 14–18 Mar 2017
- 2) Jusup M with Lee J-H, Iwasa Y: Games of corruption in preventing the overuse of common-pool resources. 64th Annual Meeting of Ecological Society of Japan, Tokyo, Japan, 14–18 Mar 2017

- 3) Mathematics of metabolic organization. 17th RIES-Hokkaido International Symposium, Sapporo, Japan, 13-14 Dec 2016

b. 招待講演（国内学会）

該当なし。

c. 一般講演（国際学会）

- 1) Jusup M with Podobnik B, Tiganj Z, Wang W-X, Buldu J, Stanley HE: Biological conservation law as an emerging functionality in dynamical neuronal networks. BIFI International Conference 2018: Complexity, networks, and collective behaviour, Zaragoza, Spain, 6-8 Feb 2018
- 2) Jusup M with Wang Z, Wang R-W, Shi L, Iwasa Y, Moreno Y, Kurths J: Onymity promotes cooperation in social dilemma experiments. BIFI International Conference 2018: Complexity, networks, and collective behaviour, Zaragoza, Spain, 6-8 Feb 2018
- 3) Jusup M with Tsuzuki A, Funo T, Inaba H, Morioka Y, Doi T, Behera S, Hashizume M, Kruger P, Minakawa N, Iwami S: Climatic phenomena and malaria incidence in South Africa: From wavelet-based data analysis to complex networks-based modelling. The International Society for Ecological Modelling (ISEM) 2017 Global Conference, Jeju, Korea, 17-21 Sept 2017
- 4) Jusup M: Network reciprocity and punishment in social dilemma experiments. Agenda 2030: Economics in a changing world, 1st International Scientific Conference on Economics in a Changing World, Umag, Croatia, 28-29 Aug 2017
- 5) Jusup M with Domingos T, Sousa T, Labinac V: Physics of metabolic organization. DEB Symposium 2017, Tromsø, Norway, 31 May-2 June 2017
- 6) Jusup M with Lee J-H, Iwasa Y: Games of corruption in preventing the overuse of common-pool resources. The 2016 Conference on Complexity Systems, Beurs Van Berlage, Amsterdam, The Netherlands, 19-22 Sept 2016
- 7) Jusup M with Liu Y, Deng Y, Wang Z: A biologically inspired immunization strategy for network epidemiology. European Conference on Theoretical and Mathematical Biology, Nottingham, UK, 11-15 July 2016
- 8) Jusup M: Incorporating the uncertainties of feeding ecology into stock assessments of valuable fish species: the case of Pacific bluefin tuna. The International Society for Ecological Modelling Global Conference, Baltimore, USA, 8-12 May 2016

d. 一般講演（国内学会）

該当なし。

e. 研究会・シンポジウム・ワークショップなど（学会以外）

- 1) 北大-日立新概念コンピューティングコンテスト (2017/11-12)。
- 2) Jusup M: Testing the fundamentals of evolutionary game theory. Yunnan University of Finance and Economics, Kunming, China, 18 Oct 2017
- 3) Jusup M: Understanding human cooperation by means of social dilemma experiments. Center for Experimental Research in Social Sciences, Hokkaido University, Sapporo, Japan, 29 June 2017
- 4) Jusup M: Social dilemmas and human cooperation. Tenure-track mixer, Hokkaido University, Sapporo, Japan, 24 May 2017
- 5) Jusup M: Cooperation in social dilemma experiments. Mini-workshop on Network and Data Science, Northwestern Polytechnical University, Xi'an, China, 25 Mar 2017
- 6) Dynamic Evolution of Complex Ecological, Biological, Social, and Economic Phenomena. Research Institute for Electronic Science Research Exchange Meeting, Hokkaido University, Sapporo, Japan, 6 Jan 2017
- 7) How do mutualisms evolve? Evolutionary game dynamics under an asymmetric strategy setup. Colloquium of Hokkaido University Department of Mathematics, Sapporo, Japan, 21 Dec 2016
- 8) Pattern formation and pattern transitions in spatial epidemiology. Theory of Biomathematics and Its Applications XIII, Research Institute of Mathematical Science, Kyoto, Japan, 14-17 Nov 2016
- 9) Evolutionary game theory and network theory for solving real-world problems. Northwestern Polytechnical University, Xi'an, China, 3 Nov 2016
- 10) Jusup M: Evaluating the potential for evolutionary adaptation to environmental stressors. Workshop on Combining Modeling and Experimental Approaches for Marine Organisms under Stress, Brest, France, 29 Aug-2 Sept 2016

4.6 シンポジウムの開催

- 1) Jusup M with Iwami S: Symposium session entitled Data analysis and modelling in ecological epidemiology, The International Society for Ecological Modelling (ISEM) Global Conference 2017, Jeju, Korea, 17-21 Sept 2017
Speakers: Marko Jusup; Dr. Ryo Yamaguchi, Tokyo Metropolitan University; Prof. Zhen Wang, Northwestern Polytechnical University, China; Prof. Kei Tokita, Nagoya University, Japan; Prof. Shingo Iwami, Kyushu University, Japan
- 2) Jusup M with Iwami S: Mini-symposium entitled The role

of cost-benefit analysis in mathematical biology, Japan Society for Mathematical Biology Annual Meeting 2016, Fukuoka, Japan, 7-9 Sept 2016

Speakers: Prof. Hiroyuki Matsuda, Yokohama National University, Japan; Dr. Tin Klanjscek, Rudjer Boskovic Institute, Croatia and University of California, Santa Barbara, USA; Prof. Zhen Wang, Northwestern Polytechnical University, China

- 3) Jusup M with Lee J-H: Mini-symposium entitled Towards data-driven mathematical biology, Japan Society for Mathematical Biology Annual Meeting 2016, Fukuoka, Japan, 7-9 Sept 2016

Speakers: Prof. Madeleine Beekman, The University of Sydney, Australia; Prof. Kazunori Yamahira, University of the Ryukyus; Prof. Takashi Kitagawa, The University of Tokyo; Yoshinori Aoki, The University of Tokyo

4.7 共同研究

a. 国内大学、研究機関との共同研究

該当なし。

b. 産業界等との共同研究

- 1) 株式会社 日立製作所との新概念コンピューティングに関する共同研究。

c. 国際共同研究

- 1) Prof. Yamir Moreno, University of Zaragoza, Spain
Topic: Human cooperation in the context of common-pool resource management
- 2) Prof. Zhen Wang, Northwestern Polytechnical University, Xi'an, China
Topic: Empirical patterns of human cooperation in the face of social dilemmas
- 3) Dr. Tin Klanjscek, Rudjer Boskovic Institute, Zagreb, Croatia
Topic: Physiological energetics of marine turtles
- 4) Prof. Madeleine Beekman, The University of Sydney, Australia
Topic: The evolution of mutualisms and parental care

d. 外国人研究者の招聘

- 1) Prof. Yamir Moreno, Spain、(2017/10/5-11)
- 2) Dr. Tin Klanjscek, Croatia、(2016/9/4-18)
- 3) Prof. Madeleine Beekman, Australia、(2016/9/4-8)
- 4) Prof. Zhen Wang, China、(2016/4/20-5/7)

4.8 予算獲得状況（研究代表者、分類、研究課題、期間）

a. 科学研究費補助金

該当なし。

b. 大型プロジェクト・受託研究

- 1) JUSUP, Marko、公益財団法人 稲盛財団、生物資源のロバスト管理のための数理生物学、2017/4/1-2018/3/31

4.9 受賞

該当なし。

4.10 アウトリーチ活動

該当なし。