



2004年(20周年記念)

日本国際賞 受賞記念講演会

2004(20th Anniversary)

JAPAN PRIZE Commemorative Lectures

財団法人 国際科学技術財団

THE SCIENCE AND TECHNOLOGY FOUNDATION OF JAPAN

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JAPAN PRIZE Commemorative Lectures

平成16年4月21日(水) 13:00～16:25
赤坂プリンスホテル別館5F 「ロイヤルホール」
13:00～16:25, Wednesday, April 21, 2004
Royal Hall, Akasaka Prince Hotel

Message

Peace and prosperity are fundamental human aspirations, and the role that can be played by science and technology towards these ends is vast.

For the development of science and technology, The Science and Technology Foundation of Japan presents Japan Prize to promote the comprehensive spread and development of science and technology. Commemorative Lectures by the Prize Laureates are held annually during the Japan Prize Week.

The Japan Prize honors those who are seen to have made original and outstanding achievements in science and technology, and thus to the peace and prosperity of mankind.

In commemoration of the 20th Anniversary of the Japan Prize in 2004, the Foundation decided to give awards to three fields of studies.

Category: Chemical Technology for the Environment
Contribution: Pioneering Work on Photochemical Catalysis and Its Application for the Environment
Laureates: Dr. Honda, Kenichi (Japan)
Dr. Fujishima, Akira (Japan)

Category: Food Production Based on Ecosystem Concepts
Contribution: Contributions to the Understanding of Shelf Ecosystems and Their Sustainable Utilization
Laureate: Dr. Keith J. Sainsbury (New Zealand)

Category: Science and Technology for Conservation of Biodiversity
Contribution: Observational, Experimental and Theoretical Achievements for the Scientific Understanding and Conservation of Biodiversity
Laureate: Prof. John H. Lawton (U.K.)

The four laureates have been invited to deliver Commemorative Lectures to the general public.

We sincerely hope that these lectures provide inspirations and encouragement to those who will be leaders in science and technology in future generations.

Prof. Dr. Kondo, Jiro
Chairman
The Science and Technology Foundation of Japan

プログラム

4月21日(水)、赤坂プリンスホテル 別館5F 「ロイヤルホール」

PROGRAM

April 21 (Wed.), Royal Hall, Akasaka Prince Hotel

開会 主催者挨拶 上田昌明 財団法人国際科学技術財団常務理事	13:00	Opening Remarks Mr. Ueda, Masaaki Executive Director The Science and Technology Foundation of Japan
本多健一博士 「光電気化学から光触媒反応へ」	13:10	Dr. Honda, Kenichi “Developing from Photoelectrochemistry to Photocatalytic Reactions”
藤嶋 昭博士 「環境改善に寄与する光触媒」	13:55	Dr. Fujishima, Akira “Photocatalysis for the Environment”
休憩(10分)	14:40	Break (10min.)
キース・セインズベリー博士 「海洋生態系の生態学的 持続利用を支える科学」	14:55	Dr. Keith J. Sainsbury “Science to support the ecologically sustainable use of marine ecosystems”
ジョン・ロートン教授 「生物多様性の保全と維持」	15:40	Prof. John H. Lawton “Biodiversity, conservation and sustainability”
閉会	16:25	Closing

Developing from Photoelectrochemistry to Photocatalytic Reactions

Electrochemistry is one of the major foundations of chemistry with a long history of research and development. It was 165 years ago when the concept of photo-effect was introduced into electrochemistry, during the time that Edmund Becquerel discovered the photovoltaic effect in 1839, while experimenting with electrolytic cells with two metal electrodes immersed in sulfuric acid to learn the effects when exposed to solar light.

Whenever we can see the object, that object is always under the light irradiation. Becquerel's study was ingenious in that he purposely studied the effects of photoirradiation, to which most researchers did not even give special attention. This is probably why he is known today as the father of photoelectrochemistry.

Studies thereafter continued in this area to gradually, but accumulate theories and facts. However, this subject never became an active field of chemistry. It was not until the late 19th century when sensitizing dye was discovered, that studies spun-off to focus on dye-sensitized cells, as the world moved into the early 20th century. In 1931, Rene Audubert, backed by his studies, predicted that electrochemical photolysis of water would eventually be possible. This is indeed an extremely ingenious foresight, considering the scientific standards of 70-plus years ago.

By the mid-20th century, the semiconductor was introduced as a device, but it was not until 1955, when W. H. Brattain and C. G. B. Garrett discovered the photoresponses on a solid-state Ge (germanium) electrode, that photoelectrochemistry became a global research topic, along with the developments in photochemistry.

In 1949, I started to study the characteristics of the oxidation reduction potential of chemicals to develop photographs under the supervision of Professor Shinichi Kikuchi, at The University of Tokyo.

With silver halide photography, exposed silver atoms are the catalyst for the silver halide silver cation to be reduced to a silver atom. The reduction level is then evaluated by oxidation reduction potential. I initially used silver electrodes to measure oxidation reduction potential. However, I conceived to use silver halide as an electrode instead of the silver electrode, thinking that silver halide would more closely resemble actual photographic development. Since development is a reaction of exposed silver halide particles, I thought it would be better to measure the electrode potential under irradiation with light. This was the first step of my research in photoelectrochemistry that started around 1960.

I tried also to reproduce Becquerel's experiment. I immersed two platinum electrodes in sulfuric acid to form a cell in which both electrodes were supposed to have nothing to do with light, then irradiated the cell with a high pressure mercury lamp. I was surprised to find that this generated roughly 50mV of electromotive force. All these findings were unbelievable and I simply couldn't understand why science in general remained uninterested in these phenomena.

Silver chloride electrodes tended to rapidly degrade, therefore, I had a hard time in reproducing the same results. I also studied the mechanism of sensitization of dye using a dropping mercury electrode polarography to learn its dynamics under light excitation.

However, this only further confirmed how difficult it was to try to study the behavior of excited molecules, back in those days.

Around this time, I could work in collaboration with Dr. Tadaaki Tani, who was studying the electron transfer interaction between excited molecules and semiconductors. Today, he is the world leading scientist in the photographic science. In those days, electrochemistry was an important area of applied chemistry. However, it still remained an area of ground state. There was practically no awareness of the importance of a light-excited state. For this reason, from around 1965, Dr. Tani and I worked together to define the concept of “electrochemistry at the excited state”. Slowly, we were able to come up with scientific classification of photoelectrochemistry.

Where,

Photoelectrochemistry =

- (1) Electrode reaction at excited state
- {Excitation of electrode
Excitation of solution
- (2) Formation of excited molecule with electrode reactions

Our group studies started systematically under the above concept, however, we gradually came to focus on the photoelectrochemistry of semiconductor electrodes and reactions of electrodes with sensitizing dye.

It was in 1966 that I met Dr. Akira Fujishima, my co-Laureate of this 2004 Japan Prize. Since, then we have worked together through good times and bad as co-researchers for over 20 years.

Semiconductor photoelectrode studies starting with Ge (germanium), soon became a

competitive area of research in Japan and abroad from the 1960's, as represented with Si (silicon), ZnO (zinc oxide) and CdS (cadmium sulfide) semiconductors. In the course of these studies, on the suggestion of Dr. Takeaki Iida studying TiO₂ (titanium dioxide) electrophotography at the laboratory next door, Dr. Fujishima attempted to test titanium dioxide (TiO₂). He constructed a cell with a single crystal rutile *n*-TiO₂ as an anode and platinum black as a cathode. Oxygen was generated without any dissolution of the anode. In other words, we succeeded in electrochemical photolysis of water.

High energy is required to break the interatomic bond of water molecules and to split the molecules into oxygen and hydrogen. However, water solutions are already dissociated into ions, therefore, only require roughly 1/4th the energy to split. When we first reported this study in Nature in 1972, the world was confronted with an oil crisis, and this study was considered as a way to manufacture hydrogen as a clean fuel and use solar energy. This attention was unexpected, but a great pleasure since this study became headline news from both aspects of clean fuel alternatives and environmental-friendliness. When the paper was first submitted we debated whether to give it the title of “Electrochemical Photolysis” or “Photochemical Electrolysis”. Eventually we decided on the former – “Electrochemical Photolysis”. Reminiscing back on those days brings back good memories.

Now that we look back to the past, we find that hydrogen was invariably disliked during the industrial electrolysis process. This was because hydrogen was always generated prior to produce the target material through electrolysis. This

wasted energy and thus, it became a major technological goal to find out the conditions that made it difficult to form hydrogen. In other words, we sought for electrode materials that yielded high hydrogen overvoltage. With the changes in times, today, we instead require materials with low hydrogen overvoltage.

a result of it showing major results as a promising environmental catalyst.

Semiconductor photocatalysis can be explained in terms of a local cell mechanism with a joint anode and cathode of a cell. Light irradiation equally gives rise to anode and cathode reactions with the same equivalence. Therefore, semiconductor photocatalysis and semiconductor photoelectrode reactions are essentially the same in mechanism, and fundamental studies in both areas progressed in parallel.

In 1971, Dr. Tadashi Watanabe joined our group of the studies on semiconductor photocatalysis. Studies other than TiO_2 (titanium dioxide) took place on CdS (cadmium sulfide), ZnO (zinc oxide) and other semiconductor particle dispersion systems. Dr. Fujishima later switched to planar fixation of TiO_2 (titanium dioxide) particles and its sustainable reaction under low intensity photolumination. As a result, semiconductor photocatalysis was epochally applied to decompose and eliminate environmental pollutants by applying the strong oxidative power of TiO_2 (titanium dioxide).

Photocatalysis is a term that was proposed in 1915 for the homogeneous reaction system. Initially, the light itself was regarded as a kind of catalysis. Furthermore, by the 1970's, some debated that it was not appropriate to use the word "catalyst" for a reaction proceeding under the action of light. Today the term has become a title of many international conferences and is a scientifically established term. We believe this is

Photocatalysis for the Environment

What is the main purpose of a real scientist? I believe that the purpose is to create a very comfortable atmosphere for all people and to enhance their life to a greater extent. The scientist must contribute to a maximum extent to fulfill this purpose.

Recently, there have been several TV and newspaper reports about photocatalysis. We have recognized that this technology is becoming more and more popular recently. For example, if we visit an electrical appliance shop, we soon realize the appearance of several products based on photocatalysis. For example, indoor air-cleaning systems based on photocatalytic systems have become very familiar in the market. These air cleaners contain special filters made from photocatalytic materials, which remove contaminants, such as those that cause bad odors, and bacteria from the indoor air, when it flows through these photocatalytic filters. That is the reason why these photocatalytic products have become very popular.

What is photocatalysis? This is our main subject. Catalysis is a phenomenon in which the properties of the catalyst material remain the same before and after the chemical reaction; however, the reaction proceeds faster in the presence of the catalyst. If this catalytic reaction happens only under irradiation, then it is called photocatalysis. This is similar to the reactions in the photosynthetic process in plants. In the case of photosynthesis, the reaction between carbon dioxide and water is enhanced under solar light to produce starch and oxygen. This reaction does not occur outside the plant, even under intense light. The chlorophyll in the plant absorbs light and enhances the photosynthetic reaction to produce starch and oxygen. However, the chlorophyll does not undergo any chemical change in this reaction. So, chlorophyll acts as

photocatalyst.

In the case of photocatalysis, titanium dioxide works as photocatalyst, similar to the chlorophyll in plant photosynthesis. Titanium dioxide is not a special material. It is widely used as a pigment in paint. However, photocatalytic reactions occurring in the paint under solar light are not desirable, because the organic binder is decomposed. In contrast, photocatalytic reactions are very important for self-cleaning applications, for example.

What is the origin of titanium dioxide photocatalysis? The study of reactions under light is the origin. About 40 years ago, when I was a graduate student, I used a titanium dioxide single crystal in the rutile form for my experiments. I cut the cylindrically shaped titanium dioxide single crystal to form a slice and heated it in a reducing hydrogen atmosphere to induce conductivity in order to use it as an electrode. I examined the electrochemical behavior of this electrode in an electrochemical cell under irradiation with a 500 W xenon lamp. I found the evolution of gas bubbles at the electrode under irradiation. The gas evolution stopped when the irradiation was stopped. I also observed the flow of current from the electrode only when the gas evolution was observed under light. As the electrolyte in my experiment was water, I assumed the gas evolved at the electrode to be oxygen, due to the photocatalytic oxidation of water. Even after a long exposure of the titanium dioxide electrodes in this experiment, the surfaces of the electrodes did not change at all. I also confirmed the absence of any change in the weight after the photocatalytic experiment.

The gas evolved in the above reaction was confirmed to be oxygen, which was produced from water but not from the titanium dioxide. We assumed that the reaction in our experiment was water electrolysis. However, the potential applied

in our experiment was not positive enough for water electrolysis, but the reaction happened, due to the irradiation of the electrode. This means that water electrolysis is possible, even at a negative applied potential, if the titanium dioxide electrode is irradiated. We named this reaction “the photosensitized electrooxidation reaction.”

By using this photoelectrochemical phenomenon, we constructed a wet-type solar cell by coupling a titanium dioxide anode with a platinum electrode, which acted as a cathode. The results obtained from this experiment were published in the journal ‘Nature’. Under irradiation with a xenon lamp, the oxygen evolution reaction occurred at the titanium dioxide anode, while hydrogen evolution was observed at the platinum cathode. While this reaction was in progress, electrical current was generated through a resistor connected between the electrodes. This means that we can construct a wet type solar cell.

By using this wet type solar cell, we started to produce hydrogen, which is a clean energy source, under solar light. To produce a large volume of hydrogen, we used a large area titanium dioxide electrode by heating titanium metal sheets on a gas burner to produce an oxide layer of one micrometer thickness. We could produce about 7 liters of hydrogen by irradiating one square meter area of titanium dioxide layer electrode in our solar cell on a fine summer day. However, we found that the calculated energy conversion efficiency was only 0.4%. Although this value is very small, the material cost is also very low in this system. This is a very interesting subject.

However, the photocatalysis phenomenon, which evolved from this fundamental photoelectrochemical behavior, has become very popular in recent days. Originating from this

concept, the antibacterial effect and the deodorizing effect have become popular in indoor air purification. Also, the decomposition of oily dirt on the surfaces of the lighting units of highway tunnels became possible. Photocatalysis is a very nice system to make a clean atmosphere. Recently, we have also found another unique property of titanium dioxide, namely superhydrophilicity. This technology has been applied to the side-view mirrors of automobiles. Now, even on rainy days, safe driving is assured, due to this superhydrophilic effect.

Photocatalysis has two unique properties. One is the strong photocatalytic oxidation power, and the other is superhydrophilicity. Therefore, titanium dioxide photocatalysis has two key components. One is titanium dioxide, and the second is irradiation. When titanium dioxide is irradiated, these two properties operate simultaneously. The first aspect of photocatalysis is the very strong oxidation power, which means that any chemical approaching the surface of titanium dioxide decomposes very easily under light. Any organic compounds at the surface decompose into carbon dioxide and water. However, in this case, the extent of the reaction is limited by the number of photons. Therefore, the temperature in this reaction does not increase as it does in the case of the combustion reaction. The photocatalytic reaction occurs at room temperature.

Another unique property of titanium dioxide is superhydrophilicity. Normally, the surface of titanium dioxide becomes fogged when water condenses on it. However, after irradiation, the water droplets on the surface do not keep their spherical shape but become flat on the surface, thereby forming a uniform film. If oil is already on the surface, the water falling on the irradiated surface penetrates under the oil and removes it

easily. By using this behavior, we can achieve an anti-fogging glass with self-cleaning properties. This technology is already being applied to side-view mirrors of automobiles in order to have safe driving.

Just recently, photocatalysis has been applied in many fields. Deodorizing, antibacterial, antifogging, and self-cleaning effects have become very attractive. Also, the photocatalytic effect has been extended to water treatment and the corrosion protection of steel. Very recently, visible light-responsive photocatalysis is becoming an active research field. If we succeed in applying this behavior, photocatalysis can be applied in even wider fields.

Science to support the ecologically sustainable use of marine ecosystems

Marine ecosystems have supported human communities and economies for thousands of years. The human benefits of marine ecosystems, historically and now, are hard to over-state. The oceans and its ecosystems provide raw materials for industry and food. They assimilate, transform and purify waste nutrients, pathogens and contaminants from human activities. They regulate climate and the composition of atmosphere. They provide the basis for increasing levels of marine-based tourism and recreation. And the coasts and ocean continue to be a source of inspiration for people.

But what is really going on in the sea? We are land animals and we usually just look at the surface of the sea. It all looks much the same and it all looks fine on the surface. But beneath the surface:

- Far too many fish stocks have been overfished; about 25% of assessed stocks world-wide and in some cases more than 90% of the stock has been removed.
- Fishing is extending further down the marine food-chain and using ever more effective technology, but in the last decade the world catch has at best remained about constant and more likely has decreased.
- Direct harvesting and by-catch in fisheries has endangered many species of marine mammals, seabirds, and turtles.
- Coastal development, sedimentation, pollution and fishing have modified or reduced many vital habitats, including mangroves, seagrasses, wetlands, corals and seabed sponges.
- Nutrients and other chemicals are modifying many marine ecosystems, and in some regions are causing huge areas to become oxygen deficient.

- There are increasing numbers of introduced marine pests in many locations.

There is an urgent need to change how we use and manage the oceans if we are to achieve the goal of sustainable development — that is meeting present needs without compromising future generations the opportunity to meet theirs.

But there are grounds for cautious optimism. As yet there have been relatively few global extinctions of marine species. And experience has shown that recovery of depleted populations and habitats is possible — although it requires focused action and takes time. But, perhaps the main reason for optimism is that many people do care about the ocean, and they do want its use to be sustainable.

How do we ensure that our use of marine ecosystems is sustainable? Science is only one part of the answer but it is fundamental for two reasons. Firstly, science provides basic understanding about marine ecosystems and the impacts of human activities on them. Secondly, science provides advice about management measures and strategies to achieve sustainable development. It is this second role that I want to emphasise here today.

A fundamental feature of predictions about marine resources and ecosystems is that they are highly uncertain. The challenge is to provide scientific recommendations that have a good chance of succeeding despite the uncertainties, to make the risks and trade-offs clear, and to identify ways to detect and correct departures from desired outcomes in time to avoid failures.

The methodology that I and others have

developed and used for this is Management Strategy Evaluation (MSE). MSE includes risk assessment and the evaluation of risk management strategies. It uses computer simulation models to test and compare strategies. To ensure realistic testing the models include all reasonable interpretations of the ecological system and available data.

MSE is commonly used to identify what to monitor, how to respond, and the expected outcomes of management. This can include environmental, economic and social outcomes. MSE also allows calculation of the value of additional information that reduces uncertainty. Different additional information may have very different cost and value to the management system.

The following four real examples illustrate application of the MSE approach.

1. The North West Shelf of Australia was intensively trawled during the 1970s and undesirable changes occurred in the species composition of the ecosystem. Models were used to evaluate different management strategies. A strategy was adopted that included closing some areas to trawling and continued trawling in others. This demonstrated that habitat modification by trawling caused the changes in fish community, and that this was reversible. The fishery is now sustainably managed using a strategy that includes restricted trawling zones.

2. There was concern about the ecological impacts of line fishing on the Australian Great Barrier Reef. In collaboration with Prof Carl Walters we developed a model of the reef ecosystem based on a range of hypotheses. We used it to develop a large scale experiment to

determine the effects of line fishing on the target species and reef ecology. The experiment has operated for the past 10y. It has demonstrated that the target species is sustainably harvested and that line fishing is not causing indirect effects on prey species or biodiversity.

3. Fisheries for toothfish recently developed around Macquarie Island in the subantarctic. This is an area of high conservation value, including marine mammals, seabirds and penguins. The impacts of fishing on the target species, by-catch, habitats and food-webs were studied and modelled to test management strategies. A strategy was developed, accepted and implemented by both fisheries and environmental management agencies. It included establishing a large Marine Protected Area and proscribed methods for determining the allowable catches.

4. A study was established on the North West Shelf of Australia to develop and demonstrate scientific methods to support integrated management of ocean uses there — including petrochemical industries, shipping, aquaculture, fishing and coastal development. A detailed model of the ecosystem, industries, and management regulation was developed. It was used to test management strategies for the separate industries and for the region as a whole. It has demonstrated that regional management strategies can be scientifically tested, despite the complexity and uncertainty of coupled ecological and socioeconomic systems.

These and other examples show that scientific methods exist to deliver reliable strategies for ecologically sustainable use of marine fisheries and ecosystems. They can deal with the wide range of ecological impacts and

situations that occur, and they do not necessarily require everything to be known. But they do require that management systems place priority on achieving ecologically sustainable use. This means using management approaches that are sufficiently precautionary for the level of understanding. We have the scientific tools to design strategies to deliver sustainable and integrated management of the world's marine ecosystems. Now we need to get on with using them.

Biodiversity, conservation and sustainability

Earth is the only planet in the entire universe where we know for certain that life exists. On this remarkable planet, approximately 1.7 million species of organisms have been described by biologists, but current work suggests that the true number of living species may be much higher than this — of the order of 10 million, possibly more. The key challenges in biodiversity research are not only to catalogue life on Earth, but also to understand how this diversity evolved, how it is maintained, and how we might hope to conserve it in the face of massive, and growing, human impacts.

The main focus of my own research spanning more than thirty years has been to try and understand ‘nature’s rules’ underpinning this diversity, and what the rules tell us about attempts to conserve it. I have not been alone in these endeavours and the lecture will explore what ecologists have learned collectively about patterns and processes in biodiversity. It will, however, concentrate on the systems I have studied personally, using insects on bracken (a globally common fern, *Pteridium aquilinum*), controlled environment facilities, mathematical models, and analyses of very large datasets assembled by others. The core of my work has been in community ecology, that branch of environmental science concerned with how many species co-inhabit a bit of ‘real-estate’ on planet Earth, and why this number, and not an order of magnitude more, or less?

By way of example, we now know that there are more species in large patches of habitat than small patches — the ‘species-area relationship’. This is hardly remarkable, but what is remarkable is its regularity. We also know that on average, species with large geographic ranges (widespread species) are more abundant where

they occur than species with restricted geographic ranges - the ‘range-abundance correlation’. This is less intuitive, and less well understood than the species-area relationship, but both have major consequences for conservation as human beings fragment habitats (creating smaller patches) and artificially restrict the ranges of most species (leading to declines in population density even where species still survive). I will illustrate both ideas with data and experiments.

These relationships set the big picture. What happens at more local scales, say within a small patch of bracken? Ecologists have for many years concentrated their attempts to understand local biodiversity on what I have called the ‘local rules of engagement between species’ — particularly interspecific competition, predation and parasitism. I have done this myself, in seeking to understand how food-webs work using mathematical models of species interactions for example. But because bracken occurs naturally on every continent in the world (except Antarctica), and because it has a different, and largely independently evolved, herbivorous insect fauna associated with it on each continent, I was able to show that the major determinants of local species richness in these assemblages of insect herbivores operate at large, biogeographic scales. The ‘local rules of engagement’ are very much second-order phenomena. There is every reason to believe that these same rules apply to many, possibly most other animal and plant communities, shifting the emphasis of community ecology from local processes to biogeographic scales.

Ecology in general is a big and diverse subject, with surprisingly little contact between its various sub-disciplines. I have never found

this satisfactory, and have particularly striven to reunite two of its major sub-disciplines, namely community ecology and ecosystem ecology. Indeed, I have argued that neither can seriously advance without them coming together. Two examples illustrate the problem. One is a growing body of data and theory showing that loss of species from local assemblages (local extinctions) can progressively impair key ecosystem processes such as net primary production and nutrient cycling. My own work in the Ecotron controlled environment facility was the first to show this experimentally, and I and colleagues subsequently extended this work into a pan-European field experiment, confirming the results across a wide range of soil-types and climates.

The second example concerns the role of organisms as ‘ecosystem engineers’ — species that create and maintain habitats for many other species. Community ecologists have essentially ignored the general rules that underpin the roles of species (like beavers) that create and maintain habitats for myriads of others by ecosystem engineering. The phenomenon is quite general, with simple rules and generalisations, and deserves much more attention from ecologists.

I will also touch on arguably the greatest contemporary challenge of all for ecologists, which is the likely impacts of human-induced climate change on communities of plants and animals, driven by rising atmospheric carbon-dioxide concentrations. Again, to predict and deal with the likely consequences, we have to adopt an ecosystem perspective, and I will illustrate emerging insights derived from the Ecotron and other experiments, not least the unexpected effects of rising carbon-dioxide concentrations themselves on soil processes and

soil organisms.

Finally, despite a huge growth in understanding the underpinning processes that determine the diversity of life on Earth from local to global scales, we are also losing species at an accelerating rate: Earth faces another mass extinction, this one driven entirely by the activities of one species — us. Climate change is partly responsible, and its impacts will grow. But the main drivers are habitat destruction, pollution, direct hunting and harvesting of species, and the sheer scale of the human enterprise. I will close by considering the sombre statistics, and point out how they pose questions about the sustainability of modern societies unless we adopt hugely different and cleverer ways of doing things. Then, and only then, can we hope to use our knowledge about life on Earth to deliver a sustainable future for all the species with which we share this remarkable planet.

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