Perspectives on emerging issues

International students studying alongside Indian students on the Bangalore campus of the Indian Institute of Management. *Photo: © Atul Loke*

Universities: increasingly global players

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Global competition but also a global family

As I am writing this essay in June 2015, 9.5 million students are simultaneously taking the *gaokao* (高考), the Chinese National College Entrance Examination giving access to university. What better illustration of the formidable importance of higher education at the beginning of the 21st century? More than ever, people are convinced today that knowledge and skills obtained at universities are crucial to personal well-being, as well as to the social and economic health of cities, nations and regions.

Universities have become institutions of a global world, in addition to assuming their traditional local and national roles. The answers to global challenges (energy, water and food security, urbanization, climate change, etc.) are increasingly dependent on technological innovation and the sound scientific advice brokered to decision-makers. The findings contributed by research institutes and universities to the reports of the Intergovernmental Panel on Climate Change and the Consensus for Action[1] statement illustrate the decisive role these institutions are playing in world affairs. Research universities also attract innovative industries. The Googles and Tatas of this world only thrive in proximity to great research institutions and it is this winning combination that fosters the emergence of dynamic entrepreneurial ecosystems such as Silicon Valley in the USA and Bangalore in India which are at the root of innovation and prosperity.

Universities themselves have become global players. Increasingly, they are competing with one another to attract funds, professors and talented students[2]. The reputation of a university is made at the global level. This trend will accelerate with the digital revolution, which is giving world-class universities an even greater global presence through their online courses.

As testimony to this evolution, global university rankings have appeared in the last ten years. They reflect both the existence of global competition and a global family of universities. The annual Academic Ranking of World Universities (ARWU) was first published in June 2003 by the Center for World-Class Universities of Shanghai Jiao Tong University, China. Quickly, other international rankings followed: the QS World University and the Times Higher Education rankings. International university rankings may often be debated but they never go unnoticed.

1. A message of scientific consensus addressed to world leaders on the need to maintain humanity's life support systems; the project is hosted by Stanford University (USA). See: http://consensusforaction.stanford.edu

2. Malaysia, for instance, hopes to become the sixth-largest global destination for international university students by 2020; between 2007 and 2012, the number of its international students almost doubled to more than 56 000. See Chapter 26.

What makes a university world class? A world-class university has a critical mass of talent (both faculty and students), self-governance and administrative autonomy; academic freedom for faculty and research, which includes the right to critical thought; the empowering of young researchers to head their own laboratories; and sufficient resources to provide a comprehensive environment for learning and cutting-edge research. Some of the top-ranked institutions are seasoned Western universities, from which younger universities might learn a few things. Most universities do not feature in these world-class rankings but they nevertheless fulfil important educational roles at the local level.

In the past ten years, many new universities – most notably from Asia– have entered ARWU's top 500, even though US universities still dominate the top positions. The past decade has seen the advent of an increasingly multi-polar academic world, as noted already in the *UNESCO Science Report 2010*.

If competition between universities is one hallmark of this new league, co-operation and collaboration between scientists is another. In recent years, long-distance scientific collaboration has become the rule: scientists now live in a hyper-connected world. One way to measure this is by examining the co-authorship of scientific papers. The 2015 European Leiden ranking of universities for their capacity to engage in long-distance collaboration shows that six of the top ten universities come from Africa and Latin America, with the University of Hawaii (USA) in the lead.

Explosive growth in brain circulation

Student numbers are exploding around the world, as there has never been a greater need for a good tertiary education. Emerging economies will have around 63 million more university students in 2025 than today and the number worldwide is expected to more than double to 262 million by the same year. Nearly all of this growth will take place in the newly industrializing world, more than half of it in China and India alone. Student migration, brain circulation and the internationalization of universities has never been higher. There were 4.1 million students enrolled at universities abroad in 2013, 2% of all university students[3]. This number could double to eight million by 2025. Given this small percentage, brain drain should generally not represent a threat to the development of national innovation systems, so brain circulation should remain as unencumbered as possible in higher education. Universities will remain in high demand around the world, at a time when public financial support is

3. This global figure masks strong variations from one region to another. See Figure 2.12.

strained in most countries. Gains in productivity will therefore be unavoidable, despite the very competitive nature of science; in particular, the emergence of university networks to enable institutions to share their faculty, courses and projects is a way forward.

Be relevant: close the innovation gap

The creation and transfer of scientific knowledge are critical to building and sustaining socio-economic welfare and integration in the global economy. In the long run, no region or nation can remain a simple 'user' of new knowledge but must also become a 'creator' of new knowledge. Closing the innovation gap is a necessary role of universities; innovation (or technology transfer) must become as important a mission as teaching and research.

Unfortunately, many countries in Africa and Asia mainly are producing fewer inventions today than they did in the early 1990s, despite healthy rates of economic growth. An analysis of patents signed between 1990 and 2010 shows that 2 billion people live in regions that are falling behind in innovation. This decline is overshadowed by the extraordinary development in India and China:[4] almost one-third of the 2.6 million patents filed worldwide in 2013 came from China alone.

Youth need to know their (IP) rights and engage in reverse innovation

This deficit in new patents in many countries is not due to a lack of entrepreneurial spirit, as many examples show, such as the re-invention of mobile banking in Africa. Rather, the gap is due to the fact that universities cannot bear the cost of research and technology transfer for lack of financial resources. According to Bloom (2006), responsibility for this relative neglect of higher education lies partly at the door of the international development community, which in the past failed to encourage African governments to prioritize higher education. An estimated 11 million young Africans are set to enter the job market each year over the next decade; efforts must be made to support their ideas, says Boateng (2015). For young people to find good jobs in the global economy, they will need skills, knowledge and will to innovate, as well as greater awareness of the value of intellectual property (IP).

One way to create the best conditions collectively for collaborative and 'reverse innovation' is for universities to work on appropriate (or essential) technology. These technologies aim to be economically, socially and environmentally sustainable; they are both high-tech (and therefore appealing to researchers) and low-cost (and therefore suited to innovators and entrepreneurs).

At the Ecole polytechnique fédérale de Lausanne, we have set up one such initiative, EssentialTech. This programme implements essential technologies in the context of a comprehensive value chain: from understanding needs to monitoring the real impact of these technologies and contributing to their long-term viability. For technology to have a significant and sustainable impact, scientific, economic, societal, environmental and institutional factors all have to be considered. This programme requires an interdisciplinary and multicultural, collaborative approach, as well as partnerships between the private sector, public authorities and civil society, particularly with stakeholders from low- and middle-income countries. Across the globe, many universities have set up such initiatives, or are in the process of doing so.

Digital disruption: a way of going global

The digital revolution is one new and disruptive way for universities to 'go global' beyond their single campuses to reach a global audience. Cloud computing and supercomputing, as well as the handling of big data, have already transformed research. They have given rise to global collaborative projects such as the Human Genome Project in the 1990s and the more recent Human Brain Project.[5] They allow for crowd-based networked science where researchers, patients and citizens can work together. In education, this revolution is increasingly taking the form of massive open online courses (MOOCs). Some world-class universities have realized what MOOCs can do for their visibility and reputation and begun offering such courses.

Two factors have contributed to the rapid rise of MOOCs (Escher *et al.*, 2014). Firstly, digital technology has come of age, with widespread use of laptops, tablets and smartphones in many countries and growing broadband penetration on all continents. Secondly, the 'digital native' generation has now reached university age and is totally at ease with the all-pervasive use of digital social networks for personal communication. The number of world-class universities committed to this digital innovation is steadily growing, as is the number of students – one MOOCs provider, Coursera, has seen the number of students almost double from 7 million in April 2014 to 12 million today. Unlike their online educational predecessors, the costs of MOOCs are borne not by students but by the institution producing the courses, which adds to their attractiveness. MOOCs allow a single university to extend its teaching to a global audience: the Ecole polytechnique fédérale de Lausanne counts 10 000 students on campus but has close to 1 million registrations worldwide for its MOOCs.

4. See Chapters 22 (India) and 23 (China).

5. This is one of the European Commission's Future and Emerging Technologies Flagship projects to 2023. See : https://www.humanbrainproject.eu

MOOCs could also alleviate the textbook gap

In the coming years, MOOCs will allow affordable, quality courses to be disseminated everywhere. On-campus education will remain fundamental to student life but universities will have to adapt to global competition and increasing demand from students for quality lectures dispensed by top universities. Universities that share their lectures, complemented by seminars and exercises unique to each location, are certain to be part of the landscape in 2020. MOOCS will foster the co-design and co-production of these courses by partner universities. One could also imagine providing a set of high-quality introductory lectures online to a network of partner institutions. MOOCs could also alleviate the textbook gap by providing freely accessible modules of knowledge produced by the best experts and stored in a Wikipedia-like repository.

The momentum created by MOOCs may also result in new educational packages. Up until now, MOOCs have been delivered as individual courses. However, they may aggregate into accredited programmes, in future. Universities – sometimes as networks – will decide on certification and perhaps even revenue-sharing. Certified courses are of great importance for professional education because employers are increasingly focusing on the potential employee's skill set rather than on a formal degree. Through MOOCs, the lifelong learning that is so crucial to knowledge societies is becoming a globally feasible target.

At first, universities feared that a few fast-moving world-class universities would take over the MOOC business to install domination and homogeneity. What we are actually seeing is that MOOCs are becoming a tool for co-operation, co-production and diversity. Competition to produce the best courses, yes, but monolithic domination, no.

The partnering of universities will happen

For many years, and understandably so, primary education was the main challenge in education. Now has come the time to recognize, in parallel, the crucial importance of the research experience and skills that only universities can deliver to students and lifelong learners.

The partnering of universities to co-produce, re-appropriate, integrate, blend and certify classes will happen across the world. The university of tomorrow will be a global and multilevel enterprise, with a lively campus, several antennae located with strategic partners and a global virtual online presence. The Ecole polytechnique fédérale de Lausanne is among those universities that have already embarked on this path.

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Physics students from Iran, Senegal, Spain, Venezuela and Viet Nam enjoying an impromptu study session on the terrace of UNESCO's Abdus Salam International Centre for Theoretical Physics in Italy in 2012. There were 4.1 million international students worldwide in 2013.

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A more developmental approach to science

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Science 2.0: the data revolution

Science is not only created using data; the principle output of any scientific investigation is also data. The science-led data revolution has allowed Web 2.0 and Science 2.0 to co-evolve. The second-generation World Wide Web (Web 2.0) has made it easier for people to share information and collaborate and, in turn, the second-generation open science movement (Science 2.0) has used these new web-based technologies to share research more rapidly with a greater range of collaborators. This growth in interconnectedness, information-sharing and data-reuse has helped to develop a modern approach to science. As Science 2.0 is maturing, it has gradually begun replacing existing methods of teaching and learning science. Primarily characterized by the exponential generation and utilization of data for scientific purposes, this paradigm shift has both assisted and benefited from this data revolution (IEAG, 2014).

Increasingly collaborative science

Researchers and academics are now sharing their data and research results across web-based platforms, so that the global scientific community can utilize them and further build upon these raw scientific datasets, through collaboration. One example of this type of collaborative science can be seen in the big data generated for climate change projections developed by using global-scale models (Cooney, 2012). Research such as this provides a case for the utilization of large datasets assimilated and compiled in different parts of the world to solve local problems. This type of big data 'downscaling' can bridge the gap between global and local effects by layering larger-scale data with local-level data. Another example is the recently digitized and openly accessible rice breeding project 3K RGP, 2014 which now provides virtual access to the genomic sequence data of 3 000 rice cultivars from 89 countries. Local researchers can use such information to breed improved rice varieties that are locally customized for distribution at farmer level, resulting in higher annual rice yields that nurture national economic growth.

The combined impact of online tools and advocacy for a culture of open science at the institutional and national levels has fueled the accumulation and sharing of big data in virtual knowledge banks. Such sharing of metadata will, for example, allow for the generation of locally relevant projections of weather patterns and the development of cultivars that can best adapt to a particular climatic condition. In this way, studies in various scientific disciplines have become increasingly interconnected and data-heavy. This has made science more dynamic and given rise to two dimensions of scientific practices.

A shift from basic research towards big science

The focus of scientific discovery has shifted from basic research to 'relevant' or big science, in order to solve pressing developmental challenges, many of which have been identified as Sustainable Development Goals by the United Nations. However, basic research is extremely important for any future scientific discovery; one classic example is the discovery of the double helical structure of DNA by Watson and Crick in 1953, which laid the foundations for the subsequent work done in the fields of genetics and genomics. A more recent example is the sequencing of the human genome, which was completed in 2003 within the Human Genome Project. Whereas the identification of the 25 000 genes in human DNA was purely a quest for knowledge, the sequencing of corresponding base pairs within the same project was undertaken to unravel the mysteries of genetic variation, in order to improve the treatment of genetic diseases.

Computer networks and online interactions which facilitate the sharing of scientific information in real time across the global research community have gradually encouraged researchers to access and build upon these results in locally customized ways to solve social challenges. The global research community is no longer pegged on searching for a new element to add to the periodic table or for a molecular base triplet that encodes an amino acid. Rather, its focus is now on the bigger picture and how research can be applied to address challenges that could ultimately threaten human existence, such as global pandemics, water, food and energy insecurity or climate change. This shift in research priorities towards a big science agenda is evident in the amount of research funds allocated to applied science. Researchers are investing more than before in turning a discovery in basic research into a commercially viable and sustainable product or technology with a potentially beneficial socio-economic impact.

Without citizen engagement, no social good can come of open data

Another shift in the focus of science from basic research to an applied and developmental approach fuelled by Science 2.0 technologies is underscored by scientists' easier access than before to big data. Access can be defined firstly in the context of inclusiveness. If basic research is to be used for the betterment of human lives, there is no better way to identify a citizen's needs and challenges and to serve the interests of that person's wider community than to involve citizens themselves in the associated developmental processes. Science can only be inclusive if all parties at all levels (government, academic and general public) are duly involved. Thus, access can be defined secondly in the context of openness. Citizens cannot participate if science is not open and transparent. Without citizen engagement, no social good can come of open data, since there will be no recognition of local needs for subsequent data downscaling and data mainstreaming. For example, a regional scientific project aiming to identify the local impact of an increase in pollution levels can only be successful if citizens are able to report on the state of their health in real time to the scientific surveyors through a virtual platform that makes them active, yet informal participants in the project. Increasingly, discoveries that support early disaster warning – such as three-dimensional simulation models – are being considered more important that those that improve the capability to handle the post-disaster recovery.

Today's interconnected and futuristic approach to science has therefore redefined open and inclusive scientific practices. What used to be a teacher–student interaction in a research laboratory has now become a virtual interaction. These days, there are many scientific experiments in which ordinary citizens are both able to access and contribute to scientific big data in real time across virtual platforms to influence scientific processes – and sometimes, government decision-making processes that affect their daily lives. Engaging citizens in this way enables the general public to take part informally in the collection and analysis of big data and to influence, for example, the local customization of a developmental technology from the West, so that it is adapted to the local needs of a community in the developing world. This kind of public participation will gradually build an educated citizenry and augment the role played by citizens in solving applied scientific problems. The term citizen science refers to the public engagement of citizens who actively contribute to science, such as by providing experimental data and facilities for researchers. This fosters greater interaction between science, policy and society and thus more open, transdisciplinary and democratic research.

One example of citizen science is the project on ecosystem services management being implemented by UNESCO and its partners, which has evident linkages to poverty alleviation. The project blends cutting-edge concepts of adaptive governance with technological breakthroughs in citizen science and knowledge co-generation. A set of environmental virtual observatories enable marginalized and vulnerable communities to participate in solving various local environmental problems (Buytaert *et al.,* 2014).

While fostering a culture of open science through the provision of access to big data underpins scientific reproducibility, it also inevitably raises the question of how this type of openness and inclusiveness can maintain accountability for the actions that result from, and affect, these openly accessible data and how the full integration of science and wide participation at all levels can go hand-in hand with respect for intellectual property rights and the avoidance of research duplication or the misuse of data, such as when citation or restrictions on commercial use are ignored.

Researchers are awash with information

With rapidly evolving technologies that range 'from genome sequencing machines capable of reading a human's chromosomal DNA (*circa* 1.5 gigabytes of data) in half an hour to particle accelerators like the Large Hadron Collider at the European Organization for Nuclear Research (CERN), which generates close to 100 terabytes of data a day), researchers are awash with information' (Hannay, 2014).

A recent survey of the research community undertaken by the DataONE project showed that 80% of scientists were willing to share their data with others in the research and education community (Tenopir *et al.,* 2011). Increasingly though, researchers working in data-intensive scientific fields, in particular, are wondering how best to manage and control the sharing of their data and where to draw the line between data transparency for the social good and the risks of an uncontrollable 'data explosion'.

Avoiding the uncontrolled explosion of big data

Global spending on scientific research amounted to PPP$ 1.48 trillion in 2013 (see Chapter 1); the investment made in publishing this research is in the order of billions (Hannay, 2014). Given that interdisciplinary and highly collaborative research fields such as bionanotechnology, astronomy or geophysics are data-intensive and require frequent data-sharing and access, in order to interpret, compare and collaboratively build upon previous research results, resources should be similarly allocated for defining, implementing and communicating about big data governance and for establishing big-data sharing protocols and data governance policies at higher levels of formal scientific collaboration. Even at the level of citizens, the possible implications of 'sharing without control' in an attempt to make science more citizen-friendly could result in citizens being bombarded with an overwhelming amount of scientific information that they can neither make sense of, nor utilize. The creation of scientific big data must therefore go hand-in-hand with big data security and control, in order to ensure that an open and inclusive scientific culture can function properly.

A workshop on data governance organized by the international Creative Commons community in the State of Virginia (USA) in 2011 defined data governance in big science as being 'the system of decisions, rights and responsibilities that describe the custodians of big data and the methods used to govern it. It includes laws and policies associated with data, as well as strategies for data quality control and management in the context of an organization'.[1] Data governance can happen both at the traditional level (universities) and at the virtual level (across scientific disciplines or within large international collaborative research projects).

A code of conduct for digital science?

Big data governance applies to all stakeholders involved in the research enterprise, including research institutions, governments and funders, commercial industries and the general public. Different stakeholders can contribute at different levels. For example, at the more formal levels, governments could create data governance policies in association with affiliated research institutes at both national and international levels. At the level of citizens, people could be provided with tailored educational resources and courses in virtual classrooms to educate them about big data governance. The beneficiaries would be students, researchers, librarians, data archivists, university administrators, publishers and so on. The recent data governance workshop also describes how this type of training could be integrated into the creation of a code of conduct for digital science describing best practices for citizen science, such as data citation and appropriate data description.

By imposing this type of data usage agreement, terms of use clauses and policies targeting funders on open knowledge banks, the way in which these data are globally searched, viewed and downloaded by those interacting with the data archive could be controlled. This would, in turn, shape and differentiate how e-discovery of scientific data takes place both at the formal levels of scientific collaboration and scientific communities, as well at the informal level of citizens.

Big data and openness for sustainable development

With evolving scientific practices nurturing a gradual shift towards virtual science, there is a lot of potential for using and processing openly accessible big data generated from scientific research to help achieve the Sustainable Development Goals adopted in 2015. For the United Nations, 'data is the lifeblood of decision-making and the raw material for accountability. Without high-quality data providing the right information on the right things at the right time, designing, monitoring and evaluating effective policies becomes almost impossible.' The analysis, monitoring and making of such policies will be vital to taking up the challenges facing humanity, as defined by the 17 Sustainable Development Goals and 169 targets comprising *Agenda 2030*.

As a specialized agency, UNESCO is, itself, committed to making open access and open data one of the central supporting agendas for achieving the Sustainable Development Goals.

A mapping exercise[2] undertaken in May 2015 gives a clear understanding of how open science and openness in scientific big data link to the Sustainable Development Goals; this exercise recalls the interconnectedness between the action line on access to knowledge adopted by the World Summit on the Information Society in 2005 and the sustainable delivery of social goods and services to improve lives and alleviate poverty – an interconnectedness that has been the guiding light for the formulation of the Sustainable Development Goals.

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1. See this workshop's final report: https://wiki.creativecommons.org/wiki/Data_governance_workshop

2. See: www.itu.int/net4/wsis/sdg/Content/wsis-sdg_matrix_document.pdf

Science will play a key role in realizing *Agenda 2030*

The* 2030 Agenda for Sustainable Development *was adopted on 25 September 2015 at the United Nations Summit on Sustainable Development. This new agenda comprises 17 agreed Sustainable Development Goals which replace the Millennium Development Goals adopted in 2000. What role will science[1] play in realizing Agenda 2030? What are the related challenges and opportunities? The following opinion piece[2] attempts to answer these questions.

There can be no sustainable development without science

Since governments have agreed that *Agenda 2030* should reflect an integrated vision of sustainable development, science cuts across virtually all 17 of the Sustainable Development Goals within this agenda. Provisions related to science are also to be found in the *Declaration*, in many of the targets accompanying the Sustainable Development Goals and in the *Means of Implementation*, including as regards national investment in science, technology and innovation, the promotion of basic science, science education and literacy, and, lastly, in the parts of *Agenda 2030* on monitoring and evaluation.

Science will be critical to meeting the challenge of sustainable development, as it lays the foundations for new approaches, solutions and technologies that enable us to identify, clarify and tackle local and global problems. Science provides answers that are testable and reproducible and, thus, provides the basis for informed decision-making and effective impact assessments. Both in its scope of study and its applications, science spans the understanding of natural processes and the human impact thereon, the organization of social systems, the contribution of science to health and well-being and to better subsistence and livelihood strategies, enabling us to meet the overriding goal of reducing poverty.

Faced with the challenge of climate change, science has already provided some solutions for a secure and sustainable energy supply; yet, there is room for further innovation, such as with regard to the deployment and storage of energy or energy efficiency. This is directly relevant to SDG 7 on affordable and clean energy and to SDG 13 on climate action.

The transition to sustainable development cannot rely solely on engineering or technological sciences, though. The social sciences and humanities play a vital role in the adoption of sustainable lifestyles. They also identify and analyse the underlying reasons behind decisions made at the personal, sectorial and societal levels, as reflected in SDG 12 on responsible consumption and production. They also offer a platform for critical discourse about societal concerns and aspirations and for discussion on the priorities and values that determine political processes, the focus of SDG 16 on peace, justice and strong institutions.

The greater accuracy of weather forecasts is one example of a scientific success story, with current five-day forecasts being about as reliable as 24-hour forecasts four decades ago. There is, nevertheless, still a need for longer forecasts and more regional applications, as well as the dissemination of forecasts of extreme weather events such as heavy rain, flash floods and storm surges, which particularly affect the most underdeveloped countries in Africa and Asia. This need relates to SDG 13 on climate action.

Although infectious diseases have been largely contained in recent decades by vaccination and antibiotics, the world still faces an inevitable rise in pathogenic resistance to antimicrobial drugs (WHO, 2014; NAS, 2013). In addition, new pathogens are emerging or mutating. New methods of treatment based on basic research into the origin of antibiotic resistance and applied research devoted to developing new antibiotics and alternatives are of critical importance to furthering human health and well-being. These issues are relevant to SDG 3 on good health and well-being.

Basic and applied science: two sides of the same coin

Basic science and applied science are two sides of the same coin, being interconnected and interdependent (ICSU, 2004). As Max Planck (1925)put it, 'Knowledge must precede application and the more detailed our knowledge […], the richer and more lasting will be the results we can draw from that knowledge' (ICSU, 2004). Basic research is driven by curiosity about the unknown, rather than being oriented towards any direct practical application. Basic science entails thinking out of the box; it leads to new knowledge and offers new approaches which, in turn, may lead to practical applications. This takes patience and time and, thus, constitutes a long-term investment but basic research is the prerequisite for any scientific breakthrough. In turn, new knowledge can lead to practical scientific applications and big leaps forward for humanity. Basic science and applied science thus complement each other in providing innovative solutions to the challenges humanity faces on the pathway to sustainable development.

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1. Science should be understood here in the broader sense of science, technology and innovation (STI), ranging from the natural sciences to technologies, social sciences and the humanities

2. This opinion piece is based on the policy brief entitled *The Crucial Role of Science for Sustainable Development and the Post-2015 Development Agenda: Preliminary Reflection and Comments by the Scientific Advisory Board of the UN Secretary-General.* This policy brief was presented to the high-level session of the United Nations' Economic and Social Council devoted to the sustainable development goals and related processes in New York on 4 July 2014 and has since been updated

There are countless examples of such transformational ideas. In medical history, the discovery of the bacterial origin of diseases allowed for the development of immunization methods, thus saving countless lives. Electricity-based light did not simply evolve from a candle; this transition occurred in steps, through new concepts and sporadic leaps forward. Accelerator-based particle physics is another example of how one invention can have unanticipated beneficial spin-offs: initially developed solely as a tool for basic research, particle accelerators are common nowadays in major medical centres, where they produce X-rays, protons, neutrons or heavy ions for the diagnosis and treatment of diseases such as cancer, thus benefiting millions of patients.

There is, thus, no dichotomy between basic and applied science, nor competition but only opportunities for synergies. These considerations are central to SDG 9 on industry, innovation and infrastructure.

Science, like music, is universal

Science, like music, is universal. It is a language that we can share across cultural and political borders. For example, more than 10 000 physicists from 60 countries work together at the European Laboratory for Particle Physics (CERN) in Switzerland, inspired by the same passion and driven by shared goals. In universities around the world, new graduate and undergraduate programmes are being designed to teach tomorrow's global problem-solvers how to work across disciplines, scales and geographies. Here, science acts as a leverage for research collaboration, science diplomacy and peace, which is also relevant to SDG 16.

Science plays a key educational role. The critical thinking that comes with science education is vital to train the mind to understand the world in which we live, make choices and solve problems. Science literacy supplies the basis for solutions to everyday problems, reducing the likelihood of misunderstandings by furthering a common understanding. Science literacy and capacity-building should be promoted in low- and middle-income countries, particularly in cases where a widespread appreciation of the benefits of science and the resources for science are often lacking. This situation creates dependence on countries that are more scientifically literate and more industrialized. Hence, science has a role to play in the realization of SDG 4 on quality education.

Science is a public good

Public good science not only brings about transformative change on the road to sustainable development. It is also a way of crossing political, cultural and psychological borders and, thus, helps lay the foundation for a sustainable world. Science may further democratic practices when results are freely disseminated and shared, and made accessible to all. For example, the World Wide Web was invented to facilitate the exchange of information among scientists working in the laboratories of the European Organization for Nuclear Research (CERN) in Switzerland. Since then, the Web has radically changed the way in which the world accesses information. CERN being a publicly funded research centre, it preferred to make the Web freely available to everybody, rather than patent its invention.

The need for an integrated approach

For the post-2015 development agenda to be truly transformative, it will be vital to respect the interrelatedness of the development issues addressed by the Sustainable Development Goals. This point was acknowledged by the Open Working Group on the Sustainable Development Goals convened by the United Nations' General Assembly during the formal negotiations which led to the formulation of *Agenda 2030*. The artificial division of *Agenda 2030's* goals, based on disciplinary approaches, may be necessary for comprehension, resource mobilization, communication and public awareness-raising. Nevertheless, one cannot insist enough on the complexity and strong interdependence of the three economic, environmental and social dimensions of sustainable development.

To illustrate the strong interrelation between these three dimensions, let us consider the following: nutrition, health, gender equality, education and agriculture are all relevant to several Sustainable Development Goals and all interrelated. It is impossible to be healthy without adequate nutrition. Adequate nutrition, in turn, is closely linked to agriculture as a provider of nutritious food (SDG 2 on zero hunger). Agriculture, however, affects the environment and, thus, biodiversity (the focus on SDGs 14 and 15 on life below water and life on land, respectively); agriculture is estimated to be the main driver of deforestation when mismanaged. Women are at the nexus of health, nutrition and agriculture. In rural areas, they are responsible for the daily production of food and for childcare. Deprived of education and thus of access to knowledge, some women are unfamiliar with the interlinkages portrayed above. Moreover, their cultural background often discriminates against their well-being when they are treated like second-class citizens. Promoting gender equality and empowering rural women will, thus, be of paramount importance to making progress in all the aforementioned areas and to curb unsustainable population growth. Science is well-placed to build bridges permitting such interlinkages, in the context of SDG 5 on gender equality.

Another example of the close interlinkages among agricultural practices, health and environment is the concept of 'one health.' This concept advocates the idea that human and animal health are closely linked. This is demonstrated, for instance, by the fact that viruses originating in animals can spread to humans, as seen in the case of Ebola or influenza (Avian flu, for instance).

Perspectives on emerging issues

Given the interdisciplinary nature of science for sustainable development, the Scientific Advisory Board to the Secretary-General of the United Nations has stressed the importance of intensifying co-operation among the different scientific fields and portraying science clearly and forcefully as a key ingredient in the future success of *Agenda 2030*. Governments should acknowledge the potential of science to federate different knowledge systems, disciplines and findings and its potential to contribute to a strong knowledge base in the pursuit of the Sustainable Development Goals.

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Science for a sustainable and just world: a new framework for global science policy?

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The challenge of global change

The magnitude and implications of human exploitation of the Earth system are becoming clearer each year to the scientists who study them and to the wider public who attempt to grasp them. The Earth's natural capital yields an annual dividend of resources that form the bedrock of the human economy and the life support system for the planet's inhabitants. However, as the world's population grows, its cumulative consumption is increasingly biting into that productive capital. Two human activities stand out, in this regard: the historical development of ever more abundant energy sources to power society and the over-extraction and over–consumption of both non-renewable and, crucially, renewable resources. These activities are not only unsustainable but have also created novel hazards. Their consequences are severe and, for future generations, potentially disastrous. We live in an era in which human society has become a defining geological force, one informally termed the Anthropocene (Zalasiewicz *et al.*, 2008; ISSC and UNESCO, 2013).

The local impact of human activity is transmitted globally through the global ocean, the global atmosphere and global cultural, economic, trade and travel networks. Conversely, these global transmission systems have a local impact that varies in magnitude according to geographic location. This results in a complex coupling between social and biogeophysical processes that has re-configured the global ecology to produce one which is novel to the Earth and to which poverty, inequality and conflict are integral. On account of multiple interdependences and non-linear, chaotic relationships that unfold differently depending on context, this coupling means that attempts to address a problem affecting one aspect of this ecology necessarily have implications for others. Society, therefore, is confronted by a global set of major converging environmental, socio-economic, political and cultural problems that must be understood as parts of a whole in providing guidance for the way in which each can be effectively addressed.

However, this is the set of problems – exemplified by the United Nations Sustainable Development Goals – that society now expects science to help solve, urgently and in ways that are both sustainable and just. Meeting this challenge will require the engagement of peoples from diverse cultures and their leaders; it will demand global responses for which neither the scientific community, nor the policy world, nor the general public is well-prepared. Whereas many sectors of society will need to become involved in this process, the scientific community will have a special role to play.

Central to the challenge is the need to de-couple growth, or even economic stasis, from environmental impact. It is becoming clearer how this might best be done through the widespread adoption of a range of proven or achievable technologies at increasingly competitive costs and of operational systems and business models operating through an enabling economic and regulatory frame. Closely tied to such necessary technological transitions, there is a need for society not only to adapt but to find appropriate ways of fundamentally transforming socio-economic systems, the values and beliefs that underpin them and the behaviour, social practices and lifestyles they perpetuate.

These complex global realities provide a powerful imperative to promote profound changes in the way that science contributes to public policy and practice.

Challenging and changing science

In the past two decades, there has been an increasing realization of the need to create public dialogue and engagement as two-way processes, if effective and equitable public policies are to be developed and implemented. However, the scale and international scope of the challenge described above require an altogether more profound approach (see, for example, Tàbara, 2013). These approaches typically cross boundaries between different disciplines (physical, social, human, engineering, medical, life sciences) to achieve greater interdisciplinarity; foster truly global collaboration embracing the full diversity of scientific voices from around the world; advance new research methods for the analysis of complex, multidisciplinary problems; and combine different types or subcultures of knowledge: specialized scientific, political/strategic, indigenous/local, community-based, individual, and holistic (see, for example, Brown *et al.*, 2010). Open knowledge systems facilitate solutions-oriented research, bringing academics and non-academics together as knowledge partners in networks of collaborative learning and problem-solving and making traditional dichotomies between, for example, basic and applied research irrelevant.

A major example of the open knowledge systems approach at the international level is Future Earth, established in 2012 by an international alliance of partners, including the International

Council for Science, International Social Science Council, UNESCO, the United Nations Environment Programme, World Meteorological Organization, United Nations University and the Belmont Forum, a group of national scientific funding agencies. Future Earth[1] provides a platform for global change and sustainability research. Through this platform, researchers from many disciplines are learning to work with non-academic partners in subject matter-based networks combining knowledge and action on oceans, health, the water– energy–food nexus, social transformations and global finance. Central to the work of Future Earth is the promotion of inter- and transdisciplinary scientific practices.

While the ultimate consequences of the runaway unsustainability of the social–ecological system are, as yet, unfathomed, there are intensified efforts to understand the system by drawing on the perspectives of all disciplines, ensuring their joint, reciprocal framing of the issues and the collaborative design, execution and application of research. At the same time, there has been a shift in emphasis beyond interdisciplinarity towards transdisciplinarity as a fundamental enabling process. Transdisciplinary research engages decision-makers, policy-shapers and practitioners, as well as actors from civil society and the private sector as partners in the codesign and coproduction of solutions-oriented knowledge, policy, and practice. It recognizes that there are multiple sources of relevant knowledge and expertise to be harnessed such that all involved actors are both producers and users of knowledge at one time or another. In this way, transdisciplinarity becomes more than a new way of infusing scientific knowledge into policy and practice, more than merely a strategic reframing of the one-way science-to-action paradigm. It is conceived as a social process of creating actionable knowledge and promoting mutual learning in ways that foster scientific credibility, practical relevance and socio-political legitimacy. It is an effort to link and integrate the perspectives of different knowledge subcultures in addressing social complexity and supporting collective problem-solving. In transdisciplinary research, scientific knowledge 'producers' cease to think of knowledge 'users' as passive information receivers, or at best as contributors of data to analyses framed by scientists. Instead, scientists integrate the concerns, values, and worldviews of policymakers and practitioners, of entrepreneurs, activists and citizens, giving them a voice in developing research that is compatible with their needs and aspirations (Mauser *et al.*, 2013).

A fundamental and, indeed, necessary underpinning for the further development of open knowledge systems is currently being created by national and international initiatives for 'open science' and 'open data' (The Royal Society, 2012). The moves towards wider public engagement in recent years have led naturally to the aspiration that science should become an overtly public enterprise rather than one conducted behind closed laboratory and library doors, that publicly funded science should be done openly, that its data should be open to scrutiny, that its results should be available freely or at minimal cost, that scientific results and their implications should be communicated more effectively to a wide range of stakeholders, and that scientists should engage publicly in the transdisciplinary mode. Open science is also a crucial counterbalance to business models built on the capture and privatization of socially produced knowledge through the monopoly and protection of data. If the scientific enterprise is not to founder under such pressures, an assertive commitment to open data, open information and open knowledge is required from the scientific community.

Challenging science policy

Do the discourses about open knowledge systems and, more broadly, of open science, amount to a new science policy paradigm or framework – one that moves away from seeing the value of science through the (often national) lens of the knowledge economy towards valuing science as a public enterprise working for a sustainable and just world?

In theory, yes. Narratives about basic concepts of science policy have indeed shifted in that direction. For example, within large parts of the scientific community, notions of scientific relevance now focus less on the language of national economic growth and competitiveness, more on the need for transformative research oriented towards finding solutions to the global challenges we face.

We have also seen changes in how the science–policy interface or nexus is understood: from a one-way delivery system based on a linear model of knowledge transfer, with its language of impact and uptake and its dualistic mechanisms of knowledge production and use (e.g. via policy briefs, assessments and some advisory systems), towards a multidirectional model of iterative interaction, with feedback loops and acknowledgement of the messy decision-making processes on both sides.

Last but not least, we are seeing shifts in the geopolitics of science and, particularly, in how we formulate attempts to overcome global knowledge divides. Capacity-building has become capacity development but both have essentially remained locked into the idea of support as a form of catch-up aid for the global South. That thinking is changing towards notions of capacity mobilization, recognizing excellence and the need to support regional science systems in order to foster truly global integration and collaboration. Has a shift towards a new science policy framework been realized in practice? There are encouraging signs of change in this direction. At the international level, Future Earth

1. see: www.futureearth.org

provides a new institutional framework for the promotion of integrated, transdisciplinary scientific practice. More importantly, perhaps, financial support for a such practice has been committed through the multilateral funding initiatives of the Belmont Forum and, more recently, through the International Social Science Council's Transformations to Sustainability Programme.[2]

At the same time, a critical reality check of prevailing science policy practices suggests the opposite. Universities, globally, have a vital role to play here. They are unique among human institutions in the range of knowledge they enfold, in sustaining and reinvigorating inherited knowledge, creating and communicating new knowledge. Only too often, though, that knowledge is still contained and communicated in disciplinary siloes, reinforced by exclusive disciplinary approaches to academic training, funding priorities and incentive mechanisms. Old ways of producing scientific knowledge are perpetuated by traditional forms of evaluation based on unyielding and inappropriate metrics, as well as enduring reward and career advancement systems. Researchers are rarely encouraged (let alone rewarded) to acquire the socio-cultural competencies and engagement skills needed to manage cross-cultural, inter- and transdisciplinary processes.

Creating the conditions of possibility

Science policy is not yet 'walking the talk' of an open knowledge, open science policy framework. The onus lies not only with universities but also with those national science policy bodies that set research priorities, allocate funding and devise incentive systems to recognize and respond to the broader imperative that such a framework entails. In particular, we need creative and co-ordinated solutions from them for a better integration of the natural, social and human sciences in fields such as global change and sustainability research. We also need dedicated support for open, inclusive processes of producing solutions-oriented knowledge in partnership with societal stakeholders. We also need science policy-makers to be critical and reflexive. Theme-focused research must not crowd out creative explorations of unregarded territory to which we owe many of the insights and technologies upon which the modern world is built and where creative solutions for a future world are likely to arise. It is, therefore, vital for there to be careful monitoring and evaluation of the difference the codesign and coproduction of knowledge between academics and non-academics makes to the practice and effectiveness of policy.

Why is this so important? Committed support for integrated, solutions-oriented, transdisciplinary science has real implications for what it means to be a scientist in the Anthropocene – for how they practice their art, how we train them, evaluate and reward them, for the kinds of career systems we put in place. This has implications for how we fund research and whether and how science can respond to current demands for it to contribute solutions to critical global challenges and to support transformations to sustainability. It will determine the role that science plays in shaping the future path of humanity on planet Earth.

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2. See: www.belmontforum.org; www.worldsocialscience.org/activities/transformations

Local and indigenous knowledge at the science–policy interface

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Towards global recognition

In recent years, local and indigenous knowledge has emerged as a new and increasingly influential contribution to the global science–policy interface. Of particular note is the recognition provided by the Intergovernmental Panel on Climate Change (IPCC) in its *Fifth Assessment Report* (2014). In analysing characteristics of adaptation pathways in the Summary for Policy-makers on *Climate Change 2014: Synthesis Report*, the IPCC concludes:

> *Indigenous, local, and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation.*

This acknowledgement of the importance of local and indigenous knowledge is echoed by IPCC's 'sister' global assessment body. The Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) established in 2012 has retained indigenous and local knowledge as an 'operating principle' that translates into the following scientific and technical function of the IPBES Multidisciplinary Expert Panel: *explore ways and means of bringing different knowledge systems, including indigenous knowledge systems, to the science–policy interface.*

Other prestigious scientific bodies with global mandates in science and policy are bringing local and indigenous knowledge to the fore. The Scientific Advisory Board to the Secretary-General of the United Nations decided at its Third Session in May 2015 *'to prepare a policy brief for the attention of the Secretary-General recognizing the important role of indigenous and local knowledge for sustainable development and providing recommendations for enhancing the synergies between ILK and science'*.

Understanding local and indigenous knowledge systems

Before going any further, it may be useful to clarify what is meant by 'local and indigenous knowledge systems.' The term makes reference to knowledge and know-how that have been accumulated across generations, which guide human societies in their innumerable interactions with their environment; they contribute to the well-being of people around the globe by ensuring food security from hunting, fishing, gathering, pastoralism or small-scale agriculture, as well as by providing health care, clothing, shelter and strategies for coping with environmental fluctuations and change (Nakashima and Roué, 2002). These knowledge systems are dynamic, and are transmitted and renewed by each succeeding generation.

Several terms co-exist in the published literature. They include indigenous knowledge, traditional ecological knowledge, local knowledge, farmers' knowledge and indigenous science. Although each term may have somewhat different connotations, they share sufficient meaning to be used interchangeably.

Berkes (2012) defines traditional ecological knowledge as 'a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment.'

Recognition as 'knowing again'

Local and indigenous knowledge is not something new. Indeed, it is as old as humanity itself. What is new, however, is its growing recognition by scientists and policy-makers around the world, on all scales and in a rapidly growing number of domains.

Recognition is the key word, not in the sense of 'discovering' what was previously unknown but rather as revealed by the word's etymology: 're' (again) + 'cognoscere' (know), meaning 'to know again, recall or recover the knowledge of …. something formerly known or felt.'[1] Indeed, today's efforts to 'know again' indigenous knowledge acknowledge the divide put in place by positivist science centuries ago.

This separation, and even opposition, of science, on the one hand, and local and indigenous knowledge, on the other, was not a malevolent act. It might best be understood as a historical necessity without which science could not have emerged as a distinct body of understanding with defined methods and an identifiable group of thinkers and practitioners. Just as Western philosophy has ignored continuities and emphasized discontinuities when constructing 'nature' in opposition to 'culture', so, too, has positivist science chosen to ignore innumerable traits shared with other knowledge systems in order to set itself apart, first as different then as 'unique' and ultimately as 'superior.'

Still today, young scientists are trained to value the scientific traits of being empirical, rational and objective, which suggest by opposition that other knowledge systems suffer from

1. See: www.etymonline.com/index.php?term=recognize subjectivity, the anecdotal and irrationality. Of course, no one can deny the impressive track record of positivist science in advancing understandings of our biophysical environment with an astounding suite of technical advances that have transformed and continue to transform, for better and for worse, the world in which we live. The division and opposition of science to other knowledge systems, and among disciplines within science itself, are no doubt important keys to the global success of positivist science.

However, compartmentalization, reductionism and specialization also have their limitations and blind spots. Have the advantages of opposing nature and culture, or science and other knowledge systems, been increasingly outweighed in recent decades by their disadvantages? Might the growing understanding and appreciation of these shortcomings be contributing to the emergence of local and indigenous knowledge in the global arena?

Local and indigenous knowledge emerging in global arena

The emergence of local and indigenous knowledge at the global science–policy interface suggests that a long period of separation between science and local and indigenous knowledge systems is coming to an end. This said, separation may not be the right term. In actual fact, the interconnections of science with other knowledge systems may never have been severed, only obscured. Science grew from local observations and understanding of how nature works. In the early days of colonial science, for example, ethnobotany and ethnozoology relied on the knowledge and know-how of local people to identify 'useful' plants and animals. Local and indigenous systems of nomenclature and classification, adopted wholesale, were often disguised as 'scientific' taxonomies. European understanding of Asian botany, for example, *'ironically, depended upon a set of diagnostic and classificatory practices, which though represented as Western science, had been derived from earlier codifications of indigenous knowledge'* (Ellen and Harris, 2000, p.182).

Not until the mid-20th century do we observe a shift in the attitude of Western scientists towards local and indigenous knowledge. This was triggered by Harold Conklin's iconoclastic work in the Philippines on *The Relations of Hanunoo Culture to the Plant World* (1954). Conklin revealed the extensive botanical knowledge of the Hanunoo which covers *'hundreds of characteristics which differentiate plant types and often indicate significant features of medicinal or nutritional value.'* In another realm and another region, Bob Johannes worked with Pacific Island fishers to record their intimate knowledge of *'the months and periods as well as the precise locations of spawning aggregations of some 55 species of fish that followed the moon as a cue for spawning'* (Berkes, 2012). This indigenous knowledge more than doubled the number of fish species known to science that exhibit lunar spawning periodicity (Johannes, 1981). In northern North America, land use mapping for indigenous land claims paved the way for advocating a role for indigenous knowledge in wildlife management and environmental impact assessment (Nakashima, 1990).

Efforts to better understand the vast stores of knowledge possessed by indigenous peoples and local communities expanded in the years to come, with a particular focus on biological diversity. The now well-known article 8(j) of the Convention on Biological Diversity (1992) contributed to building international awareness by requiring Parties to '*respect, preserve and maintain knowledge, innovations and practices of indigenous and local communities embodying traditional lifestyles relevant for the conservation and sustainable use of biological diversity.*'

But local and indigenous knowledge was also gaining recognition in other domains. Orlove *et al.* (2002) unveiled that Andean farmers, through their observations of the Pleiades constellation, could predict the advent of an El Niño year with an accuracy equivalent to that of contemporary meteorological science:

> *The apparent size and brightness of the Pleiades varies with the amount of thin, high cloud at the top of the troposphere, which in turn reflects the severity of El Niño conditions over the Pacific. Because rainfall in this region is generally sparse in El Niño years, this simple method (developed by Andean farmers) provides a valuable forecast, one that is as good or better than any long-term prediction based on computer modelling of the ocean and atmosphere.*

Recognition of the veracity of local and indigenous knowledge has also emerged in another domain: that of natural disaster preparedness and response. One of the most striking examples relates to the Indian Ocean tsunami that tragically took over 200 000 lives in December 2004. In the midst of this immense disaster, accounts began to emerge of how local and indigenous knowledge had saved lives. UNESCO had its own direct source of understanding, as a project had been running for many years with the Moken peoples of the Surin Islands in Thailand. The 2004 tsunami completely destroyed their small seaside village, but no lives were lost. After the tsunami, the Moken explained that the entire village, adults and children, had known that the unusual withdrawal of the ocean from the island shore was a sign that they should abandon the village and move rapidly to high ground. None of the Moken present on the Surin Islands had themselves witnessed *laboon*, their term for tsunami but, from the knowledge passed down through generations, they knew the signs and how to respond (Rungmanee and Cruz, 2005).

Biodiversity, climate and natural disasters are but a few of the many domains in which the competence of local and indigenous knowledge has been demonstrated. Others could be mentioned, such as knowledge of the genetic diversity of animal breeds and plant varieties, including pollination and pollinators (Lyver *et al*., 2014; Roué *et al*., 2015), knowledge of ocean currents, swells, winds and stars that is at the heart of traditional open ocean navigation (Gladwin, 1970) and, of course, traditional medicine, including women's in-depth knowledge of childbirth and reproductive health (Pourchez, 2011). That human populations around the world have developed expertise in a multitude of domains related to their everyday lives seems self-evident, yet this fount of knowledge has been obscured by the rise of scientific knowledge, as if science needed to marginalize others ways of knowing in order to ensure its own global growth in recognition and influence.

Where to from here?

The emergence of local and indigenous knowledge at the global level brings with it many challenges. One relates to maintaining the vitality and dynamism of local and indigenous knowledge and practices in the local communities from which they originate. These other knowledge systems are confronted with a multitude of threats, including mainstream education systems that ignore the vital importance of a childhood education anchored in indigenous languages, knowledge and worldviews. Recognizing the risks of an education centred only on positivist ontologies, UNESCO's programme on Local and Indigenous Knowledge Systems is developing education resources rooted in local languages and knowledge with the Mayangna of Nicaragua, the people of Marovo Lagoon in the Solomon Islands and for Pacific youth.[2]

Of a different nature is the challenge of meeting expectations raised by the recognition, in multiple domains, of the importance of local and indigenous knowledge. How, for example, might local knowledge and knowledge-holders contribute to assessments of biodiversity and ecosystems services, or to understanding the impact of climate change and opportunities for adaptation? Moving beyond recognition to address the 'how' has become a major focus in science–policy fora. Having reinforced recognition of the importance of local and indigenous knowledge for climate change adaptation in the IPCC's *Fifth Assessment Report* (Nakashima *et al*., 2012), UNESCO is now collaborating with the United Nations' Framework Convention on Climate Change to identify tools for, and methods of, bringing indigenous and traditional knowledge, alongside science, into the response to climate change. Last but not least, a Task Force on Indigenous and Local Knowledge has been established to provide IPBES with appropriate 'approaches and procedures' for bringing indigenous and local knowledge into global and regional assessments of biodiversity and ecosystem services. UNESCO is assisting in that effort through its role as the technical support unit for the task force.

2. See: www.unesco.org/links, www.en.marovo.org and www.canoeisthepeople.org

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