Scientific literacy, public engagement and responsibility in science

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Abstract
This work addresses the issue of scientific literacy and its connection to the responsibility of scientists in relation to public engagement. The points of departure are, first, the notion of science as a global public good, and, second, developments in the past few decades driven largely by the digital revolution. The latter lend a particular urgency to initiatives aimed at promoting scientific literacy. Arguments are presented for reassessing approaches to public communication. The particular example of genome editing is provided as a vehicle for highlighting the challenges in engagement involving the scientific community, policymakers and broader society.

Keywords
Ethics, public engagement, responsibility in science, science literacy, scientific literacy

I. Introduction
The word ‘science’ is derived from the Latin ‘scientia’, meaning ‘knowledge’. It is an apt term to describe the endeavours and struggles through recorded history that have aimed at understanding the world in which we live, whether for its own sake or motivated by reasons of utility.

Scientific developments have taken place in fits and starts and have gathered momentum over the centuries, and the 20th century was characterized by an explosion in scientific progress. For some time now, scientific activity and progress have been dominated by professional researchers in universities and in public and private laboratories, and scientific research has become ever more specialized and sophisticated.

Science interacts with and influences the lives of individuals and communities. Dramatic progress has been accompanied by equally impressive applications, largely beneficial, although the use of scientific knowledge for harmful purposes is, as ever, a reality.

The question then is: to what extent is it desirable, or essential, that broader society become conversant with scientific knowledge, that is, be scientifically literate? A justification for scientific literacy as a pursuit might be motivated by reasons that include the utilitarian, the aesthetic and the cultural, and by a vision of society in which individuals and communities are well placed to weigh the
impacts and consequences of scientific knowledge on their daily lives, health and safety.

This paper argues, first, that the nature of scientific and technological developments in the 21st century demands greater urgency in addressing the goal of promoting scientific literacy; second, that the social contexts that characterize this century should be a central consideration in shaping scientific literacy initiatives; and third, that it is a responsibility of the scientific community to be at the forefront of scientific literacy initiatives.

This work starts at the beginning, as it were, by considering what is meant by a scientifically literate individual or community. The link to scientific responsibility is made by examining the idea of science as a global public good: what is meant by this, and how it relates to scientific literacy. This leads naturally to an interpretation of scientific responsibility and the role of the scientific community in engaging in activities aimed at promoting scientific literacy.

The contemporary context in which the public learns about scientific developments is almost unrecognizable from that of a mere two to three decades ago. It is one that is shaped to a significant extent by the digital revolution, particularly by the explosion in information. It is important to understand this context, which is rich in opportunities for making science more accessible, but also fraught with developments that threaten the very basis of scientific literacy – for example, the propagation of pseudoscientific views and misinformation.

Scientific progress is often accompanied by ethical questions that might challenge cultural or religious norms. Citizens are best placed to consider their position on such questions when they have access to the relevant scientific background and details, presented in comprehensible fashion. These considerations apply as much to individuals as to groups in civil society, and to policymakers in government and elsewhere.

These contextual considerations provide the basis for the argument that the responsibility of scientists applies not only in communicating scientific knowledge beyond their own communities, but also in the manner in which public engagement is most effectively pursued. The 21st century context requires a reconsideration of the themes that are most urgent. The thread thus runs from science as a public good to the responsibility of scientists in promoting scientific literacy.

Complete trust in scientists is a foundational requirement for successful and enduring interactions between scientists and broader society. Although trust in science overall remains high, there are at any given time threats to such a trusting relationship, and the scientific community has a responsibility to ensure that it earns that trust by upholding the values of science and conducting itself in a responsible and ethical manner.

How then does one go about communicating with the public? The terms ‘public’ or ‘society’ take no account of the multidimensional and complex nature of the challenge. The relevance of science, and of scientific literacy, to society is brought into focus where scientific progress interfaces with cultural, social and religious norms and particularly when challenged by apparent tensions at those interfaces. An inability to recognize such complexity may well lead to efforts that turn out to be counterproductive. Thus, having reviewed the notion of scientific literacy in the 21st century context, it becomes important to set and act upon preconditions for successful engagements between scientists and society.

The objective of this work is to develop the themes referred to here in a systematic way, with an emphasis on the connections and interrelationships between scientific literacy and the responsibilities of scientists in relation to public engagement. The somewhat abstract development is ratified by considering the particular example of genome editing, a truly 21st-century development that offers the promise of major benefits for humanity, yet one that is accompanied by serious ethical questions, the resolution of which must involve not only scientists and policymakers, but also civil society.

While the attempt here is to address issues of scientific literacy across a broad range of sectors of society, the major topic of scientific literacy at the school level and its intersection with science education lies beyond the scope of this work, and is not treated here.

2. What do we understand by scientific literacy?

The notion of scientific literacy refers in broad terms to the idea of scientific values, knowledge, discoveries
and their applications, as well as the fundamental underpinnings of the scientific method, being familiar among the broader public. This aspiration carries with it a number of substantial questions: for example, what do we mean by ‘familiarity’? How broadly should this knowledge be diffused within the general public? To what extent should sectors such as policymakers, public and private industries and NGOs be treated as entities through which specific, tailor-made scientific literacy initiatives are developed? And, how does one go about engaging with the public in order to convey scientific knowledge effectively and to achieve the desired ends?

It is useful to turn to some sources for comprehensive definitions of scientific literacy.

Holbrook and Rannikmae (2009) provide an overview of scientific literacy that includes a discussion of the range of definitions to be found. To fix ideas, the OECD PISA (Programme for International Student Assessment) framework defines scientific literacy as ‘the ability to engage with science-related issues, and with the ideas of science, as a reflective citizen’ (Organisation for Economic Co-operation and Development (OECD), 2019). It continues by describing as scientifically literate a person who has acquired the competencies to engage in reasoned discourse about science and technology, evaluate and design scientific enquiry and interpret data and evidence scientifically. Though the framework addresses school education, it provides sets of definitions and perspectives that are useful in the context of the focus of this work.

The corollary to such a definition is that a scientifically literate individual is in a position to engage in such knowledge in the course of contributing in and contributing to debates of a cultural nature, as well as on issues that affect well-being at various levels: personal, family, community and nation.

What would one expect of a scientifically literate citizen? At a regional workshop for UNESCO’s Project 2000+: Scientific and Technological Literacy for All (United Nations Educational, Scientific and Cultural Organization (UNESCO), 1993), scientific and technological literacy was defined as ‘the ability to creatively utilize science knowledge in everyday life to solve problems’. The workshop materials described 17 ‘traits of a person considered scientifically and technologically literate’, among which are the expectations that the scientifically literate individual

- Uses concepts of science and technology . . . in solving everyday problems and making responsible decisions in everyday life, including work and leisure;
- Engages in responsible personal and civic actions after weighing possible consequences of alternative options;
- Defends decisions and actions using rational argument based on evidence;
- Engages in science and technology for the excitement and the explanations they provide;
- Displays curiosity about and appreciation of the natural and human-made world (UNESCO, 1993).

Thus, the vision is of a society in which individuals, groups and communities, although not professionally trained as scientists, are in a position to appreciate the substance and beauty of scientific developments and draw on such knowledge in the course of contributing to decision-making processes that affect society as a whole.

3. The link to science as a global public good

The rationale for the promotion of scientific literacy may be self-evident, but it is important that it has a rigorous grounding. A point of departure for such a rationale is that of science as a public good. Public goods are defined as resources that are both non-excludable and non-rivalrous (Wikipedia, 2020). Non-excludability refers to the criterion that individuals cannot be excluded from the use of the resource or would not be required to pay for use. A public good is non-rivalrous in the sense that use by one individual does not reduce availability to others. Further, the good can be used simultaneously by more than one person.

The benefits of global public goods reach across borders, generations and population groups. Examples include fresh air, knowledge, lighthouses, national defence and flood control systems.
Take as a further example the eradication of smallpox: the whole of humanity benefits, both present and future generations. Success in responding comprehensively to the threat of global climate change would secure intergenerational as well as geographically widespread benefits.

Science is a global public good, an aspiration which, significantly, has been adopted as the vision of the International Science Council (2020a), a body whose stated mission is to serve as the global voice of science. The route from science as a public good to scientific literacy is determined by considering the implications of this vision for scientists and the corresponding responsibilities.

The scientific community has a responsibility, in the first instance, to disseminate scientific knowledge within its ranks, through journals and other specialist media, and in doing so to adhere to the editorial and ethical guidelines pertaining to the review, publication and assessment of such work. In exercising that responsibility, it is important that the great diversity of the scientific community be taken into account: the strength and depth of scientific systems and the extent to which they are properly resourced vary significantly. The spirit and the letter of science as a global public good therefore require that scientists take such variations into account: the need to ensure that communities have access to and participate in developments in science, regardless of their local circumstances: whether they are distant from and poorly connected to the loci of major activity, for reasons of geography or levels of economic development or whether there are factors such as gender or age that result in their marginalization.

The responsibility of scientists goes beyond dissemination within their own communities. There is a responsibility on the shoulders of the scientific community to ensure that scientific knowledge and results are made accessible in broader society, including the general public and policymakers. Furthermore, the mere dissemination of material that is inevitably specialist and technical in nature cannot suffice; the means by which such dissemination is carried out must take into account the target communities by ensuring that the information is not only accessible, but also comprehensible.

An understanding of the way science works is a prerequisite for successful public engagement. The effective dissemination of scientific information beyond the scientific community presupposes an understanding within broader society about the nature of scientific investigations, the provisional nature of scientific evidence, uncertainties in models and their interpretation and the process, generally complex with multiple paths, of arriving at consensus positions (Torcello, 2016; see, for example, Section 7 and, more broadly, the consideration of public communication strategies that seek to unite the ‘deficit model’ and ‘cultural cognition’ approaches, with climate change as the working model).

Scientific investigations are seldom straightforward, and errors do occur. A scientifically literate populace should have an awareness of these nuts-and-bolts aspects of scientific enquiry and of the various nuances of scientific research, and it is vital that scientists, for their part, do not paper over such imperfections and complexities in their engagements with the public. An open approach builds trust and better understanding, and makes for sustainable two-way engagements (International Science Council, 2020b).

This bedrock is especially relevant when the context for public engagement is an emergency or threat that has potentially ruinous and life- and livelihood-threatening implications for broad swaths of society, and in respect of which scientific advice is a central component of steps to combat the given threat. Recent examples would include the Fukushima disaster in Japan, the Ebola crisis in West Africa and the SARS-CoV-2 pandemic, an ongoing threat, the like of which has not been witnessed for more than a century. The response by governments to such threats necessarily includes, or should include, close collaboration with scientists. The resulting actions inevitably have a direct impact, sometimes devastating, on local communities, because of which scientists have a major responsibility to promote a good understanding of the scientific underpinnings of policy decisions and to ensure effective three-way communication involving scientists, society and policymakers.

4. The context in which public engagement takes place

The nature of public engagement and the objectives of scientific literacy are, to a great extent, shaped by
the contemporary landscape of societal and environmental conditions as well as technological developments. This is no less true of the 21st century, which is witnessing the dramatic impact of what has been referred to as the digital revolution (Hodson, 2018): that is, the rapid growth of, and increasingly easy access to, computers of ever-increasing power and speed, accompanied by a similarly rapid growth in communication via online news media and various forms of social media.

These developments have irrevocably changed the circumstances under which news and information are communicated.

The ease of access to and the ability to participate in such communication is, of course, a good thing. Nevertheless, what might at first be regarded as a multiplicity of unalloyed benefits is accompanied by features that threaten to undermine the objective of sharing information that is honest, truthful and supported by evidence. Take, for example, the growth of the dissemination of manipulated, biased or fabricated information, lacking in editorial norms and processes for ensuring the accuracy and credibility of information. Communication via social media has ballooned, with high volumes, rapid communication and fact-checking being bypassed. Bots – software applications that run automated tasks over the internet – magnify the spread of fake news and contribute to items ‘going viral’. It is estimated that more than half of all web traffic consists of bots (Lazer et al., 2018).

The term ‘fake news’ is understood in this context to refer to information that is deliberately, fabricated and often distributed in ways that mimic the formats of news media, thus lending it the appearance of credibility. There is an overlap between misinformation (false or misleading information) and disinformation (false information that is purposely spread to deceive people) (Lazer et al., 2018).

The widespread dissemination of fake news and misleading and biased information feeds new expressions of science denialism, casts doubt on the need for scientific understanding and interpretation and threatens evidence-informed decision-making in policy and public action. A significant proportion of such denialist interventions can be attributed to the industrial sector, primarily as a means of defending products such as tobacco and toxic chemicals (Michaels, 2020; Oreskes and Conway, 2010). It constitutes a fundamental – and potentially pernicious – attack on the public value of science, and in turn undermines efforts to build a robust global science system and to advance science as a global public good.

The dissemination of pseudoscientific arguments might be regarded as a subset of fake news, given features such as a lack of supporting evidence, erroneous arguments and a general incompatibility with the scientific method.

Furthermore, the politicization of some issues at the science–society interface has contributed to the emergence of ‘post-truth populist epistemology’ (Rosenfeld, 2018) and the adoption of ideological positions or anti-scientific stances on such topics as climate change, genetically modified organisms (GMOs) and vaccination that are diametrically opposed to and in conflict with the scientific consensus on these issues – all this through the use of sophisticated strategies to undermine the collective judgement and position of scientists.

The propagation of ‘dissenting theories’ (De Melo-Martin and Intemann, 2018) and related unscientific models and campaigns to discredit science pose a real threat to progress and are in conflict with the values of science and efforts to ensure the well-being of society. They require that scientists fundamentally re-evaluate their role in relation to broader society. The scientific community has the responsibility to be vigilant in the face of such anti-scientific acts, to make publicly known their lack of validity, and to advocate strongly for scientific values and the scientific method.

The nature of information flow during the SARS-CoV-2 pandemic provides a good example of challenges that are central to much of the digital age. There has been a deluge of information on the pandemic across various news and social media platforms. Some of this is based on good scientific practice, but a significant proportion falls under the heading of misinformation and is based on weak or no evidence or is deliberately misleading. Such misinformation is often interwoven with scientifically credible and accurate information, rendering it all the more difficult to identify trustworthy and reliable sources (Wasserman, 2020).
These developments all pose a fundamental threat to the integrity of processes by which science informs policymaking. They emphasize the importance of continuing engagement by the scientific community, which must maintain complete transparency and be explicit about both evidence-based information and potential shortcomings. They also give greater urgency to effective communication and engagement with society at large; a scientifically literate society is one that is in a better position to evaluate information and distinguish between items that have a genuine scientific underpinning and those that are pseudo- and anti-scientific in nature.

5. Public engagement and responsibility in science

Scientists have a role that goes beyond being mere brokers of scientific information within the scientific community. Consistent with the view of science as a global public good, the responsibility of the scientific community extends to communicating scientific information and results broadly, in civil society and among policymakers. There are, of course, significant challenges associated with conveying scientific information of a usually highly technical and specialized nature in a manner that renders it comprehensible to individuals who are not scientists. The link here to scientific literacy is clear: a scientifically literate person would be expected to have a sufficiently good understanding of the underlying scientific material to appreciate its beauty and ingenuity. Furthermore, where relevant, this informs their approach to making responsible decisions, whether in the workplace or as a private individual.

One would expect the means of public engagement to be directed also towards an understanding of the evidence that underpins the scientific results. That, in turn, presupposes a proper understanding of the scientific method: of the nature and role of evidence, and of what is meant by scientific consensus. These considerations are especially important in the present-day context of mis- and disinformation: the scientific community, as well as science communicators, have an especially important responsibility to ensure that the general public is well acquainted with the way in which science works, even if the arcane technical details are beyond any but specialists.

Similar considerations apply to the role of uncertainty in science. Scientific progress and discovery are replete with uncertainties in the interpretation of data and the extent to which a hypothesis stands up to scientific tests. Mathematical and related models are, by their nature, approximations of phenomena and should be open to robust testing and revision as necessary. Such an apparent lack of certainty, if not properly understood, may well engender mistrust or scepticism outside the scientific community. It is therefore important that the public gains a good understanding of those features of the scientific method in addition to being informed about scientific developments. Such a well-informed public is then equipped with the means by which to weigh up options for actions as individuals or as members of social and other groups, and to defend such decisions by appealing to the evidence and the means by which scientific consensus has been achieved. The role of scientists in this context lies well within the domain of advocacy: for the scientific method, and for arguments that underpin scientific consensus.

Much of the development that has taken place during the 20th and 21st centuries may be attributed to the use and application of scientific results. There is thus no doubt about the beneficial nature of science. Science also has harmful outcomes, intended or otherwise. The notion of dual-use research of concern captures this Janus-like nature of science. The term has been conceived in the context of life sciences research that is intended for benefit, but which might easily be misapplied to do harm (see, e.g. World Health Organization, 2013). Potentially harmful uses of science are present in most, if not all, scientific disciplines, in addition to residing in the means by which scientific information is communicated.

The domain of science advice lies at the interface of science and public policy formation, with the role of scientists being that of providing the scientific evidence and information relevant to the development of such policies. The role of scientists does not extend to that of advocating for one or another policy direction: in formulating policies, policymakers ordinarily take into account not only scientific input, but also a range of other considerations, such as public perception, timing and affordability. This particular arena of public engagement is a complex one, in which policymakers generally take advice from a
range of sources that might include academies and formally appointed scientific advisers, as well as ad hoc advisory groups.

Whatever the make-up of the advisory cohorts, in the first instance trust in the scientific community by policymakers is essential. This is a sine qua non for robust discussion, for example, about the place and significance of science within the multifaceted forms of advice reaching the policymaker. A cautionary note on steering clear of anything that might resemble advocacy also plays an important role here in engendering such trust. Not the least complex aspect of this form of public engagement lies in the responsibility to present and interpret scientific material in a manner that allows its key aspects to be understood by a broad range of recipients, whose backgrounds are diverse and, in all likelihood, not scientific in nature.

The above issues have come to the fore most forcefully in conventional and social media from early 2020, with the unprecedented impact of the SARS-CoV-2 viral pandemic. The public has witnessed the role of scientists in advising governments, particularly the complexities of that role: diverse groups of scientists advising through formal and other routes, disagreement between groups of scientists on modelling the pandemic and its likely evolution, and measures to combat the spread of the pandemic and treat the seriously infected. This has been good, from the point of view of broader society, which has been able to witness first hand, as it were, the complexities of science advice in action during an emergency.

The impact of the pandemic, not only on the health of individuals, but also on social and economic aspects of their lives, will have brought home the importance of broader society being able to weigh up science advice and the responses of policymakers, and being able to identify instances of misinformation, deliberate or otherwise – although the latter is not straightforward even for scientists.

In addition to being better placed to engage with the immediate consequences of the pandemic, a scientifically literate society is one that is in a good position to also engage with its aftermath: plans for recovery, and for transformations – some of them no doubt permanent – that will inevitably follow. Policymakers would be better placed to manage and form policy in a context of uncertainty, with the need to weigh and synthesize advice from different specializations.

6. Trust in science

Complete trust in science and the work of scientists is a sine qua non for giving substance to the vision of science as a global public good. An implicit social contract requires that scientists uphold a set of scientific values, engage with integrity and honesty in their work, act ethically in a professional capacity and communicate scientific work with integrity, respect, fairness, trustworthiness and transparency. Both the beneficial and the harmful consequences of scientific knowledge and its applications should be communicated openly. Furthermore, in their engagements with policymakers, impartiality in informing policy is essential to engendering trust (Kofler, 2019).

That there are breaches of those ethical standards is clear from well-documented and reported cases of scientific misconduct (The Economist, 2013). Such cases threaten the reputation of science and efforts to engender trust and seriously compromise the lines of communication between scientists and broader society. Instances of misconduct include fraud, fabrication and falsification. A further problem is manifested by multiple reports of a lack of reproducibility (Brainard and You, 2018), which may or may not be a result of misconduct but which serve to undermine the ethical foundations of science if not addressed immediately, for example, through a retraction.

Reassuringly, there has been a rapid increase in actions taken by journals to identify cases of scientific misconduct and seek retractions where appropriate. The data shows a rise in the number of retractions since the beginning of the 21st century – a trend that has been attributed at least in part to more focused oversight on the part of journals – as well as an increase in the number of journals engaged in such oversight. It appears also that the number of retractions is slowing down, again possibly as a result of more rigorous review procedures on the part of journal editors. Such actions, as an example of regulation by the scientific community, serve to
restore trust where it might have been undermined by the various practices of scientific misconduct (Brainard and You, 2018).

There is evidence to suggest that, notwithstanding the lapses in ethical behaviour on the part of a few scientists, the levels of trust in science remain relatively high and are on the increase, albeit with considerable variation by region and in relation to such factors as gender and socio-economic status (Wellcome Trust, 2019).

7. Communication

There is substantial variation in the extent of engagement with science within broader society. For example, understanding of the concepts of ‘science’ and ‘scientist’ has been found to vary from very high proportions in high- and some middle-income countries to much more modest numbers in low-income countries, although the issue is too complex to be reduced to a numerical proxy for levels of understanding of science. Furthermore, while a significant proportion of the world’s population believes that science benefits them, there is substantial variation by region in the extent to which that belief is held (Wellcome Trust, 2019).

This provides some context that ought to inform initiatives aimed at communicating science beyond the scientific community.

The traditional view of science communication has been turned upside down by unprecedented developments in social trends. In the era of ‘fake news’ and the politicization of scientific issues, scientists and science communicators may well be regarded as partisan sectors having a particular ideological or political stance, rather than as conveyors of expert, evidence-based knowledge. This context demands a re-examination of the relationship between scientists and society and of approaches to communicating science to non-scientists.

An important component of communication about science relates to responses to the anti-science environment and the need for a vigorous defence of the scientific method, coupled with a creative and compelling articulation of the social, political, economic and cultural values of science. Scientists have a responsibility to ensure that policymakers and the general public are in a position to evaluate arguments in such a way that they can determine the difference between evidence-based scientific views on which consensus has been achieved and those that lack a scientific foundation.

The challenge, then, has as much to do with ‘what to communicate’ as with ‘how to communicate’. The history of engagements between science and society features multiple examples of approaches by scientists that took no account of the social, cultural or religious contexts of communities. On the contrary, there are many examples of approaches that have rightly been labelled ‘elitist’ and have seriously undermined efforts at building a trusting relationship among scientists, broader society and policymakers (Lynas, 2018).

In engaging on controversial and politicized scientific issues, it is vital to respect feelings, moral intuitions and cultural contexts (Lynas, 2018), while being alert to the role of special interests that may serve to degrade public discourse. Merely repeating scientific opinions and outcomes, either more clearly or more loudly than usual, is not the way to success. Direct engagement with those outside the scientific community and a deeper understanding of how people receive and respond to messages both individually and collectively are vital. This requires leadership at the nexus of science education, communication and public outreach, sociology and behavioural sciences (for an exploration of these and other issues related to the public communication of science and technology, see, e.g. Schiele, 2018).

Scientists are motivated to make major discoveries but may be reluctant to engage in communication outside their particular communities. They may, often with justification, feel ill-equipped to engage in such communication. This highlights the precise nature of the scientific community’s responsibility with regard to communication: rather than it being the responsibility of every single scientist to be an active and effective communicator, the interface with the public and policymakers is a communal responsibility and decisions about the means of communication and of those scientists who engage in such communication should be guided by criteria that ensure that competent, if not gifted, communicators are in the vanguard of such work.
Like most other enterprises, scientific work – whether research, teaching or outreach – is accompanied by incentives and rewards for work of high quality. These considerations are relevant in approaches to engage in communication: beyond monetary reward, recognition in universities and research institutions of the value of such work and its relevance should be considered when scientists are hired or considered for promotion.

The communal responsibility extends also to the need to forge links and sustained relationships with various forms of media, whether through science journalists or otherwise. The dilemma that scientists face is one of a deluge of information through formal and social media. There is a need to surmount the relevant obstacles to ensure that scientific news of interest and importance to the general population is granted space in this crowded environment. Unless strong, enduring relationships are established with individual journalists, editors and others, communication through the media is patchy, lacking in visibility, and will ultimately fail to reach the target readerships in the numbers expected.

8. The relevance of a scientifically literate population to societal development: The case of genome editing

For a more concrete perspective on issues relevant to science and society, consider the example of gene and germline editing – a dramatic scientific development that promises major benefits but one which also poses serious ethical questions.

The year 2012 saw the advent of CRISPR, a powerful tool for transforming a bacterial immune system into a fast and versatile genome editor that can alter DNA sequences and modify gene functions (Vidyasagar, 2018). The method has multiple actual and potential applications: in medicine, for example, in treating genetic defects; and in agriculture, in developing drought- and disease-resistant crops (Lallanilla, 2019).

The advent of CRISPR has been followed by a multiplicity of applications and an explosion of further scientific work and accompanying publications, as well as patent applications. While the highest number of publications are from the United States, China is a close second – a development that can be linked to substantial government investment in new facilities and ambitious research projects (Cohen, 2019a, 2019b, 2019d). In particular, researchers in China publish twice as many CRISPR-related agricultural papers as those in the United States.

There has also been some controversy, arising from the widely reported news that a researcher had carried out a clinical application of CRISPR to edit the genes of an embryo so as to render it immune to HIV (Cohen, 2019c). That has been condemned in the scientific community as an instance of serious scientific misconduct.

The regulation of genome editing is still in its early stages, in which work on crops leads the way, partly because such research presents fewer risks and ethical dilemmas than medical applications, such as genetically engineering animals for transplanting organs. Nevertheless, there is some way to go with regard to developing appropriate regulations in the domain of agriculture. For example, a European court has made CRISPR subject to the same stringent testing conditions as GMOs (Ledford, 2019). On the contrary, the United States Department of Agriculture exempts genome-edited plants from regulations covering GMOs as long as the editing is carried out by inducing mutations that could have occurred naturally and not by transferring DNA from other species. Most of the world has no specific regulations covering CRISPR-modified food (Cohen, 2019c). The matter continues to be hotly debated.

This is the situation that confronts not only the scientific community, but civil society at large as well as policymakers at national and supranational levels. It exemplifies the urgent need for carefully constructed and comprehensible engagements with broader society.

The urgency lies at the very least in the substantial ethical issues involved in gene editing, and more particularly germline editing, as the latter would allow characteristics to be passed on to future generations. It involves ethical and societal issues of which the general public should be aware, notwithstanding the technical and scientific complexities: Are we crossing a red line because of the possibility...
of altering our species? What are the views in broader society that would be central to considerations entertained by policymakers, on eugenics-like goals: designer babies with superior intelligence or sporting abilities? What are the margins of safety in carrying out CRISPR-based interventions, for example, if DNA cuts are made in the wrong place?

While there is some way to go before regulatory frameworks are implemented to cover much, if not all, of the globe, some current initiatives are worth noting. A committee has been set up by the World Health Organization to examine the scientific, ethical, social and legal challenges associated with human genome editing (World Health Organization, 2020). Also, the US National Academies and the UK’s Royal Society have reported on the work by a commission convened to ‘develop a framework for scientists, clinicians and regulatory authorities to consider when assessing potential clinical applications of human germline genome editing, should a society conclude that heritable human genome editing applications are acceptable’ (US National Academies, 2019).

9. Concluding remarks

There is an understandable expectation that success in addressing major challenges requires unprecedented levels of cooperation between scientific communities, across the natural and social sciences, along with policymakers and, crucially, civil society. These considerations apply equally to such challenges as climate change, the agenda captured in the Sustainable Development Goals, and the SARS-CoV-2 pandemic. A necessary, though by no means sufficient, condition for success in meeting those objectives is a society that is broadly scientifically literate, has an understanding of how science works, and one which can participate in processes that shape policies and programmes that affect people’s lives.

The 21st century brings with it significant and unique challenges to efforts aimed at the promotion of scientific literacy. However, its potential benefits for broader society are massive and unprecedented: a better understanding of the impact of scientific developments on health and well-being, the ability to engage knowledgeably on issues at the intersection of science and cultural norms, and to share in the enjoyment and excitement that accompany scientific discovery.

Author’s note

This article is based on a keynote presentation delivered at the first World Conference on Science Literacy in Beijing in September 2019.

Declaration of conflicting interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author received no financial support for the research, authorship, and/or publication of this article.

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