scrutiny. New laws or guidelines may be needed to check the marketing of certain services.

Many countries face the challenge of developing effective policies that both respect the ethical standpoint of diverse publics and enable the exploration and application of biomedical technologies. China should be given an equal voice in the global discussion about how best to achieve this. Encouragingly, more dialogue is starting to happen. In an unprecedented move, the Chinese Academy of Sciences joined the US and UK scientific academies in organizing the first international summit on human gene editing last year.

Establishing appropriate governance for research in the life sciences is hard for everyone given globalization, the pace of technological advances, the complexity of domestic regulatory ecosystems and a growing international movement to make deregulated markets — not government officials or bioethicists — the arbiters of quality and ethicality. We must therefore strive for a better understanding on all sides of the efforts that different countries are making, and of how they can work together to develop a consensus on international governance. Good rules drive good science. ■

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EPA

The Five-hundred-meter Aperture Spherical Telescope in Guizhou is due to be completed in September.

Boost basic research in China

Improving the quality, integrity and applicability of scientific research will underpin long-term economic growth, writes **Wei Yang**.

China's economy relies on innovation. Developing technologies, improving efficiency and creating and implementing new scientific knowledge can invigorate industry and help society. China's recent economic slowdown, however, calls for a gear change in how the nation innovates.

For several decades, short-term and focused technological research and development (R&D) has been the main driver in China. Large public grants were channelled to promising or urgent areas to deliver new turbine engines, high-speed trains, solar panels or drugs in 5–10 years. Now China must take a longer and broader view, and nurture its science roots.

Basic research — studies that create scientific knowledge and technologies that can be subsequently developed, translated or applied — has a conflicted image in China. Progress has been enormous (see *Nature* **481,** 420; 2012): China's share of research papers worldwide (as counted in Elsevier's Scopus database) grew from 2.5% in 1997 to 18.8% in 2015 — but severe criticisms persist (see ref. 1 and *Nature* **463,** 142–143; 2010). For example, critics say that China's universities have become paper mills induced by metrics that value quantity over quality. Impact remains low: few chemical reactions or processes are named after Chinese scholars, even though the nation now publishes more papers in chemistry than any other. Research misconduct — including ghost-writing and reviewing — has been rife, as evidenced by retractions of papers by Chinese authors from BioMed Central, Elsevier and Springer journals in the past two years.

Industrialists and some government officers complain that many academic studies, such as in pure mathematics or fundamental physics, are irrelevant to the nation's economy or society. Scientific and technological progress contributed to only 55% of economic growth in China in 2015, compared with 88% in the United States in the same period. And China spends relatively little of its total R&D budget (public, industrial and private) on basic research — just 4.7% in China compared with 24.1% in France, 17.6% in the United States and 12.6% in Japan in 2013.

Improving the quality and integrity ▶

of basic research must be the focus of national efforts to boost innovation in China. Quality needs to matter more than quantity, and integrity is the best way to ensure quality. Applicability to technological development justifies drawing more resources into basic research. As the head of the National Natural Science Foundation of China (NSFC), a leading national government funding agency for basic-science research, I call for a sustained focus to bring about such a change by 2020.

EMERGING POWERHOUSE

China is rising rapidly up the global scientific ranks by every measure — quantity and quality of output, R&D spend and increased collaboration (see page 452). For example, China's share of high-impact works (the top 0.1% of papers in Scopus rated by citations) has grown, from less than 1% in 1997 to about 20% now.

"Raising the bar on quality must be the top priority."

Founded in 1986 with a starting budget of just 80 million yuan (US$12.2 million), the NSFC has expanded more than 300-fold to allocate 24.8 billion yuan in 2016. It funded 62.1% of Chinese research papers, or 11.5% of global academic output, in 2015. The foundation's mission is to be a 'FRIEND' of scientists: fair in reviews; rewarding in fostering research; international in global participation; efficient in management; numerous in grants; and diversified in disciplinary coverage.

But beyond the buoyant statistics, basic research in China has been slow to develop. For example, there is only one science Nobel laureate from mainland China. And the nation's research lags behind other countries in terms of citations — its Field Weighted Citation Impact measure was 0.86 in 2015, below the world average of 1.0.

Raising the bar on quality — higher citations and more major breakthroughs — must be the top priority. Put another way, China needs to raise the altitude of its basic research landscape and form high mountains.

Agreed metrics are needed to track progress. Current measures are heterogeneous and do not work equally well across China's vast and diverse academic landscape. The country has 1,000 research institutions capable of basic research, each with a different focus, and more than 1,000 universities, each with a different blend of research and teaching. For example, Tsinghua University in Beijing receives nearly 5 billion yuan in annual research grants from all sources, whereas some regional colleges have research budgets of only a few million yuan per year. Measuring publication numbers might work well for a young institute that publishes ten papers a year in relevant international journals, but may eventually distort the disciplinary mix of a large university that publishes 10,000 papers a year in diverse journals.

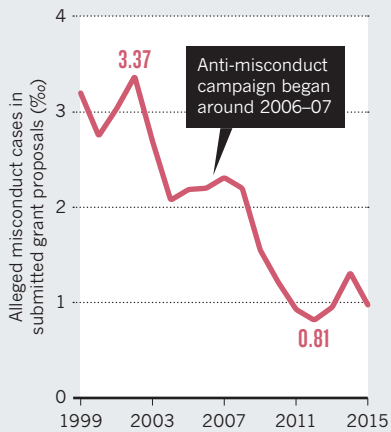
So, in practice, each institute must decide for itself what is most important to track. It might choose to look at whether a project or person is producing many publications, whether the work has high impact or is highly cited, if a project is globally significant or is a major scientific breakthrough. Each institute must plot a trajectory that is consistent with its history, current status and future goal. Evaluation needs must be reassessed as a project matures, and as the institute upgrades. In most cases, when institutes are managing their progress healthily, this 'soft' approach will work. Interventions such as campaigns to reward high-quality work might be needed for those that deviate from the research commonwealth.

Universities need to implement metrics wisely and clarify their aims (see D. Hicks *et al. Nature* **520,** 429–431; 2015). The Chinese Academy of Sciences (CAS) has taken a lead: some 15 years ago, it was the first in China to include citation in its assessment metrics, leading to an exponential growth in high-impact works. And three years ago, CAS directed each of its 104 research institutes to concentrate on one mission, three near-future breakthroughs and five long-term directions.

But setting targets that are too rigid can skew or hinder research. More institutes recognize that emphasizing publication numbers pressures researchers to write lots of incremental papers rather than a few good ones. Merit-based academic evaluations — that account for international recognition, representative works and impacts to the field — can avoid this. Long-term development, which may be slow but steady, must be distinguished from short-term gains that lack sustainability. Many universities and research institutes are downsizing the proportion of researchers' salaries that are based on performance (from more than 70% to less than 30% in extreme cases), so that a higher percentage goes towards rewarding merit.

MISCONDUCT ALLEGATIONS FALL

China is on a long march to research integrity, as shown by data from funding agency NSFC.



SOURCE: NSFC

Another question is how best to apportion basic research funds. Should science address societal 'grand challenges' or test bold concepts? Should resources be pooled or shared among many individuals? One answer is to cover several bases. For example, the NSFC invests 70% of its funding in blue-skies research, 10% on supporting talent and 20% on major research projects for scientific challenges and new research facilities.

Later this year, the ministry of education will launch a blueprint for a 'double excellence initiative' to drive China's universities and academic programmes towards world-class standards, such as by assembling high-quality teams. It is likely that the evaluation for universities will change to reward the achievement of a few top-quality departments rather than many average ones — with similar goals to the UK Research Excellence Framework. Many universities are adjusting their academic structures and realigning leading researchers in anticipation.

REINFORCE INTEGRITY

China is enduring a long march to research integrity[2]. The United States tops the league table of retracted papers (see retractionwatch.com), partly owing to its formidable quantity of scientific publications, but retractions from China are growing. The countries have taken slightly different educational approaches to reinforcing integrity[3]. In China, research misconduct tends to be portrayed in black-and-white terms — scientists are either on the moral high ground or cast into the ethical abyss. In the United States, educators analyse grey areas by discussing case studies with early-career researchers in class. Both countries can learn from each other.

Research misconduct in China is driven by several forces[2,3]. These include competition (owing to the rapid expansion of researcher numbers) as well as assessment criteria — the need to publish in international journals encourages the use of language services or ghostwriters, and quantification encourages research outputs to be split up and published separately (known as salami-slicing). Other drivers include strengthening of ethical values such as animal rights, and insufficient provision of ethical codes in areas such as genetics and big data.

For the past decade, the China Association for Science and Technology, the education ministry and the NSFC have run a well-publicized anti-misconduct campaign in the Chinese scientific community. It is having results (see 'Misconduct allegations fall'). Most research institutions now have procedures in place to tackle suspected or confirmed ethical breaches, and a zero-tolerance policy has been enforced in some, such as Zhejiang University in Hangzhou (see

China's DAMPE satellite launched in December 2015; others are scheduled to follow this year.

XINHUA/REX/SHUTTERSTOCK

Nature **481,** 134–136; 2012). The proportion of allegations of misconduct is declining even though more attention is being given to actively detecting cases. Similarities between submitted proposals and published dissertations are also going down. The culture of new researchers is changing from 'why not cheat' to 'it is not worth getting caught'.

To go further requires changes on three fronts: attitude, structure and methodology.

A change in attitude — from covering up misconduct to exposing it — is essential. The NSFC is implementing a similarity check for submitted grant proposals and now publishes an annual press release detailing notorious misconduct cases. It is also investigating cases of ghostwriting and reviewing. Since 2000, we have evolved our policies on information handling, from guarding review confidentiality to transparency in research evaluation. Each panel is required to monitor the healthy conduct of review in its discipline, by voting on the fairness of their fellow panellists' judgements, for example.

Structural changes within institutions are crucial to separate administrative and academic powers and prevent corruption. For instance, the NSFC has exercised various practices that might be applied in other funding agencies. Agency administrators are no longer involved in academic reviews. NSFC staff members are only authorized to access information that is relevant to their duties, and an independent council of senior academics has been set up to counterbalance the administrators. In many institutions, external advisers are now used to avoid conflicts of interest, academic committees are being given more power, and committees have been formed to safeguard research and clinical ethics.

Methodology changes can remove the soil that nourishes research misconduct. A nationwide campaign against overly quantified measures of research is under way. Caps on human-resource costs are being lifted. A streamlined funding architecture needs to be achieved, which reduces fragmentation in grant sources and mandates that all grant reviews are conducted by professional institutions selected by a joint committee rather than by administrators. We also need to use more external reviews by international peers, and account for indirect research costs.

PRIORITY TOPICS

Which areas of basic science look most promising to develop in the next five years?

The NSFC's plan for 2016–20 includes a list of areas, breakthroughs and interdisciplinary hotspots in which China could deliver fast. Examples are the 'Langlands programme' for mathematics that links number theory, geometry, analysis and theoretical physics, such as at the Academy of Mathematics and Systems Science, CAS; and the deep underground Earth-physics laboratory near Jinping, Sichuan, that might detect dark matter. There is also the Five-hundred-meter Aperture Spherical Telescope (FAST) in Guizhou, southwest China, which is due to be completed in September; and 24 scientific satellites planned for the next 5 years (4 of which are due to launch this year) that will advance astrophysics, cosmology and Earth sciences.

Other promising areas and institutes include molecular chemistry and quantum catalysis for chemistry, which is a focus of the Dalian Institute of Chemical Physics at CAS; quantum computing for information science at the University of Science and Technology of China in Hefei; and neural circuits and brain science in Shanghai's biomedical sciences and innovation complex. The National Center for Protein Sciences (the PHOENIX Center) in Beijing and Shanghai is focusing on proteomics; and teams are working on gene editing, molecular approaches to cancer, and infectious diseases. A multidisciplinary effort is needed to stimulate the country's 'green science' — Earth, ocean and environmental science.

MUCH TO DO

For basic science innovations to benefit the economy, the full chain of development — from the initial research to technology, products and the market — must be nurtured. Not all research will bear fruit beyond the lab; some is curiosity-driven. But where possible, new knowledge should either be turned into technology or translated from one field to others.

The NSFC is feeding the source. The rest of the chain is being encouraged by the Ministry of Science and Technology, through its major National Initiatives for Technology and Engineering (16 of which run to 2020 and 15 that extend to 2030) and National Key Research Projects (36 launched this year). These programmes link researchers, developers and venture capitalists. Examples include addressing air pollution, increasing the use of low-carbon energy in chemical engineering and deep-sea stations for ocean exploration.

Barriers between research and commercial development are being dismantled by new policies. These include the recent revisions of knowledge-transfer laws, which assign the benefits of public-funded projects to the researchers and their institutions (similar to the US Bayh–Dole Act). Researchers thus gain incentives of fame and wealth.

In summary, four issues need attention. First we must incentivize, not discourage, Chinese scientists for making big scientific breakthroughs. These take time and endurance, as the recent detection of gravitational waves illustrates. Areas such as basic physics and astronomy need master plans for long-term development.

Second, we must develop and adopt an assessment strategy using appropriate metrics for evaluating merit.

Third, we must create a healthy, congenial academic ecology. We should let researchers spend time on research, rather than overload them with paperwork or leave them to fend off allegations and slog over grant finances.

Finally, we must devise a business model for China that identifies and cultivates applicable research findings. There are many miles to go before we rest. ■

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