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Divergence, Convergence, and Innovation: East-West Bioscience in an Anxious Age

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Abstract: If current economic growth trends persist, the "Great Divergence" between Western Europe and East and South Asia in per capita income that commenced two hundred years ago will close sometime this century. Key to the closing will be greater accessibility to technology and higher education in East and South Asia and the relentless diffusion of knowledge including in the biosciences. Advances in the biosciences are poised to contribute in a major way to Thomas Malthus's four necessities of human life – food, fiber, fuel, and building materials – as well as to human and animal health, biodiversity conservation, and environmental remediation and sustainability. Powerful new biological technologies like genomics and synthetic biology are just beginning to be applied in ways that can sever the link between economic growth and carbon pollution. Precise genomic editing of cereal grains could equip rice, wheat, and maize with nitrogen fixation capabilities, thus reducing the need for synthetic fertilisers with their environmental and atmospheric costs. East and South Asia, facing major food production challenges, ecological limits, pollution from fertiliser use, and drought from climate change, may take the lead over the West in adopting innovative food crop technologies.

Keywords: bioscience, innovation, energy, ecosystems, genomics, GM crops

Two centuries ago Britain and Western Europe began to leave the rest of the Eurasian continental landmass behind in per capita income (Maddison 2006). Historian Kenneth Pomeranz called the phenomenon that separated Europe from China economically the "Great Divergence" (Pomeranz 2000). He borrowed the term from political scientist and historian Samuel

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P. Huntington who used it to illuminate how the Western world overcame pre-modern economic growth constraints and surged ahead of the East beginning in the nineteenth century.

Some scholars, Pomeranz included, attribute the divergence to colonialism, intercontinental trade, and especially energy production from the burning of Carboniferous biomass in the form of coal, which was plentiful in England's West Midlands where the Industrial Revolution began. Pomeranz reminds us that technological innovation and economic development occur in an ecological context. He takes into account the exploitation of land-based biosystems for food, fiber, fuel, and building materials production – English economist Thomas Malthus's four necessities of life, which were in competition with each other for land – and the ecological constraints to economic growth such exploitation posed. Colonial resources and conveniently located coal served to alleviate these ecological constraints in Britain and set the country on a path of scientific and technological advance with supportive social and political institutions for entrepreneurs.

Environmental history is one of the fastest growing sub-disciplines of the field (Burke 2009).[1] It is destined to become more important with the growing environmental consequences from massive extraction and burning of fossil fuels, the damming of rivers, deforestation, and the production and use of nitrogen-based fertilizers and cement. "If the eighteenth century pushed the limits of the biological old regime, the nineteenth century and especially the twentieth century shattered them" (Pomeranz 2009).[2] The biological new regime, as Pomeranz describes it, is distinguished by half of the growth in the human population occurring in the past thirty years, half of all net water withdrawals in the past fifty years, a fifteen-fold increase in annual energy consumption since 1900, and unprecedented environmental degradation and adverse impacts.

Twenty-first century history, when it is written, will further entwine the economic and ecological storylines of the human experience. It will also provide a bookend for the "Great Divergence" of the previous two centuries, given current global trends in economic growth, advanced education, and technological innovation (Dervis 2012). The world economy's center of gravity has been migrating eastward for three decades, reflecting rapid growth in incomes of the vast populations of China, India, and the rest of

East and South Asia (Quah 2011) and producing anxiety in the West over its eroding economic leadership since 1980. The gradual convergence in East-West per capita income, uneven as it is,[3] will continue to be influenced by trade, capital investment in the East, the rapidly emerging Asian middle class, and the East's greater accessibility to higher education and technology than ever before. Technological convergence among nations and between different parts of the world may be abetted by free trade and foreign direct investment, but it is fundamentally a process of the diffusion and sharing of knowledge – "the public good par excellence" (Piketty 2014).

Environmentally sustainable economic growth will require putting knowledge of life code, cellular processes, biosynthesis, and biological regeneration to practical use. The biosciences are in the midst of a convergence of their own – with information technology, nanotechnology, microelectronics, materials, artificial intelligence, robotics, architecture, and design. The field is poised to contribute in a major way to Malthus's four necessities of human life – food, fiber, fuel, and building materials (bio-based construction materials). That will occur on top of the contribution of the genomic science, molecular and synthetic biology, regenerative medicine and other biological technologies make to human and animal health, biodiversity conservation, and environmental remediation and resilience (OECD 2009; Chaturvedi and Srinivas 2014; Hoffman and Furcht 2014; Hoffman 2014).

Technological innovation is responsible for more than half of the growth in advanced economies by most accounts.[4] Though biotechnology was pioneered in the West, today it is a global enterprise, with major hubs in China, Hong Kong, India, Japan, Singapore, South Korea, and Taiwan in addition to Europe, the Americas, and Australia (Hoffman and Furcht 2014). The future distribution of entrepreneurial bioscience will depend on the forces of technological innovation, urbanisation, globalisation, and research investment. These forces are overcoming the historic inability of developing countries, many of them in East and South Asia, to adopt new technologies and employ them efficiently to achieve economic productivity gains (Clark and Feenstra 2001; Dabla-Norris *et al.* 2013). But productivity gains in and of themselves are not enough. Achieving them through more efficient energy use will be essential to reduce the burden fossil-fuel combustion places on natural biosystems and the environment, a burden that pulls investment and energy away from producing goods and services to abatement and cleanup activities and pollution-related health care (Laitner 2013). The economic impact of Anthropogenic climate change, the "ecological bill" for the "Great Divergence," makes forecasting economic growth increasingly precarious.

Biology has been called "the biggest science," with the most scientists, the most funding, the most scientific results, the most ethical significance, and where there is the most to learn given its billions of years of experimental results involving self-replicating organisms (Kelly 2006). The "bioeconomy" can be understood as the set of economic activities relating to the invention, development, production and use of biological products and processes (OECD 2009). An emerging bioeconomy across Eurasia and around the world will mark the century ahead. As developing economies become wealthier they contribute in an ever-larger way "to pushing the technological frontier forward," say U.S. Federal Reserve economist John Fernald and Stanford University economist Charles Jones. They cite South Korea and China as examples of countries showing more rapid growth in research spending than the U.S., Europe, and Japan (Fernald and Jones 2014). Some 40 years ago China produced very few PhD's in science and engineering; by 2010 China was producing a quarter more PhD's than the United States. The fact that China and India represent more than one-third of the world's population prompted Fernald and Jones to pose a question: "How many future Thomas Edisons and Steve Jobses are there in China and India, waiting to realise their potential?"

As the "Great Divergence" was set to commence, Adam Smith wrote in *The Wealth of Nations* that China "has been long one of the richest, that is, one of the most fertile, best cultivated, most industrious, and most populous countries in the world. It seems, however, to have been long stationary." What was true in 1776 when Smith published his book and for two more centuries is no longer true. "In the United States and in the West, you have a certain way," Jun Wang of BGI (formerly Beijing Genomics Institute) told Michael Specter for Specter's story "The Gene Factory" about the Shenzhen-based genome sequencing giant's bid "to crack hunger, illness, evolution – and the genetics of human intelligence" among other goals. "For the last five hundred years, you have been leading the way with innovation," said Wang, BGI's chief executive. "We are no longer interested in following"

(Specter 2014). Indeed, the center of gravity for technology investment may well be in the middle of the Pacific Ocean, the midpoint between the China's bustling east coast cities with their numerous technology firms and the American west coast with technology hubs running from Seattle to San Diego (Oakley 2015).

Innovation and Convergence in the Genomic Exchange Era

Five hundred years ago, with China slipping from its earlier scientific pre-eminence, the rapid rise of global trade spurred by the spice trade, species exchange, and the introduction of novel food crops and biological materials and fibers was a boon to both urban development and capitalism in Europe. The Columbian Exchange linked continental ecosystems together, facilitating the global dispersion of plants including crop plants, animals, insects, invertebrates, allergens, and infectious microbes between the Old World and the New World (Crosby 1973). It launched what some biologists consider the beginning of a new biological era: the *Homogenocene* arising from the homogenising of ecosystems and loss of biodiversity (Samways 1999). The introduction of the potato to Europe from Peru may have accounted for a quarter of the growth in European population and urbanisation in the eighteenth and nineteenth centuries (Nunn and Qian 2011), easing ecological and population pressures and contributing to the incomes and productivity surge in the West.

Today spices like cardamom, cassia, cinnamon, ginger, nutmeg, pepper, and turmeric that spurred global trade in the European "Age of Discovery" are being intensively studied, particularly in India, for genomic markers to assist plant-breeding programmes (IISR 2011). The genomes of key crop plants in the Columbian Exchange have been fully or nearly sequenced. They include apple, banana, barley, bell pepper, cacao (chocolate), carrot, cassava (manioc), chili pepper, cotton, grape, maize, orange, papaya, peanut, pineapple, potato, pumpkin, rice, rubber, sorghum, soybean, squash, sugar beet, sugarcane, tomato, and wheat (Hoffman and Furcht 2014; Hoffman 2014). So have many domesticated animals in the exchange, including cat, chicken, cow, dog, goat, guinea pig, horse, pig, sheep, and turkey. The genomes of pathogens responsible for cholera, malaria, measles, smallpox, typhus, yellow fever, and other infectious diseases that devastated New World populations in the post-Columbian period have also been sequenced

(Hoffman and Furcht 2014; Hoffman 2014). Meanwhile, hundreds of thousands of human beings of various ethnic stripes, infants included, have been decoded over the past decade (Regalado 2014)[5], with the number expected to increase exponentially as sequencing technologies grow in productivity and decline in price (Wetterstrand 2015).

In our Genomic Exchange era, animal, plant, and microbial as well as human genetic and regulatory sequences travel around the world over high-speed data networks. Genomic sequence information about crop plants, livestock, natural materials and fibers, and pathogens is of great value for agricultural productivity, bio-based materials manufacturing, industrial bioprocessing, and biodiversity conservation as well as for disease diagnosis, treatment and prevention. Innovators can access such information from public sequence repositories like the National Institute of Health's (NIH) GenBank[6], which holds DNA and RNA sequences from hundreds of thousands of species. China's National Genebank in Shenzhen[7], which BGI established and operates, aims to become a comprehensive collection, banking, and sharing resource of biological specimens and bioinformatics data from humans, animals, plants, and microorganisms. BGI is also a leading participant in the Earth Microbiome Project[8], a multidisciplinary effort to determine the functional and evolutionary diversity of microbial communities across the globe and to produce a global Gene Atlas.

The Genomic Exchange era has the potential for creating new bioindustries based on the knowledge of life code and how the code builds and maintains proteins, cells, and organisms. The practice of technological innovation in the industrial era – the systematic application of ideas, inventions and technology to markets, trade, and social systems – is now being joined with the code of life, DNA, and the basic unit of life, the cell. Data systems are ramping up to handle the expected 'big data' deluge from whole genome sequencing and the promise it holds for precise, individualised medicine, personal health self-monitoring devices and apps, and next-generation drug development. The American technology entrepreneur and academician Vivek Wadhwa who studies how education, immigration, and entrepreneurship drive innovation makes a poignant observation: technologies involving Micro-Electro Mechnical System (MEMS) sensor-driven mobile health devices, nanobiology-based diagnostic platforms, 3D bioprinting, genomics, and DNA sequencing and synthesis are advancing at exponential rates "even as their prices fall and footprints shrink" (Wadhwa 2015).

Innovation is poised to improve efficiencies, lower costs, and spur entrepreneurial activity in the $10 trillion global healthcare industry. In some cases, the developing countries can innovate faster than developed countries, the so-called leapfrog effect, because their governments are actively working to reform their health systems and they face lower regulatory hurdles (PwC 2015). Open innovation will serve as an entrepreneurial accelerator in these efforts because the diffusion of knowledge, the "public good par excellence" in the words of economist Thomas Piketty, is the greatest force for technological convergence among nations. The Genomic Exchange era will feature the inter-organisational sharing of anonymised genetic and biological data, the electronic linking of genotypic and phenotypic information in medical records, and device-driven patient empowerment and public health. With their promise of superior diagnostics, targeted therapies, and disease prevention, whole genome sequencing and whole exome sequencing are beginning to transform health care systems, a growing number of which are building sequencing capabilities in-house or partnering with industry.

In the West, Britain is proceeding to sequence 100,000 genomes through its National Health Service in partnership with Genomics England. The Obama administration in the U.S. launched a precision medicine initiative in 2015 aimed at decoding the DNA of one million volunteers. The genomics entrepreneur J. Craig Venter and his new company Human Longevity, Inc. aim to sequence one million genomes by 2020 (Boulton 2015). In the East, BGI announced plans for a "Three Million Genomes Project" consisting of one million people, one million microorganisms, and one million plants and animals (Hardisty *et al.* 2013). On a much smaller scale, Singapore is performing deep whole genome sequencing of one hundred healthy Malays, an Austronesian group that is not represented in the 1000 Genomes catalogue of human genetic variation (Wong *et al.* 2013). Singaporean and British researchers have conducted whole genome sequencing or whole exome sequencing of several hundred South Asians in search of genetic variants underlying susceptibility to disorders such as type-2 diabetes and cardiovascular disease, which are prevalent in India and constitute a growing burden on its health care infrastructure (Wong *et al.* 2014; Chambers *et al.* 2014).

As technical barriers to human DNA sequencing decrease, as sequencing accuracy and depth grows, and as the cost of whole-genome sequencing approaches $1000, whole genome and whole exome sequencing will be used extensively in clinical medicine. Both can aid clinical diagnosis, reveal the genetic basis of rare familial diseases, and inform disease biology and drug response (Dewey et al. 2014). These technologies are also expected to uncover genetic findings of potential clinical importance in healthy individuals including infants. Perhaps more than any other sequencing service, BGI is positioning itself to be out front when genome sequencing takes hold in the clinic. Its sequencing horsepower, housed in a former shoe factory in the once sleepy fishing village of Shenzhen, has drawn the notice of multinational pharmaceutical firms with which BGI has a growing number of collaborations. One is the Asian Cancer Research Group (ACRG), jointly established by Lilly, Merck, and Pfizer. ACRG's goal is to build a knowledge bank of cancers common in Asia by generating comprehensive open-source genomic data sets to accelerate drug discovery.

BGI chief executive Jun Wang revealed in early 2015 that his sequencing powerhouse is planning to gather and bank genomic, transcriptomic, epigenomic, metabolomic and microbiomic data from one million people, an unprecedented Million Omics Database Project (Heger 2015). The scientific pre-eminence China once possessed, chronicled by the historian, biochemist, and embryologist Joseph Needham in his seven-volume *Science and Civilization in China*,[9] has not been forgotten in the Middle Kingdom.

Biomolecules, Brainpower, and the Shifting Currents of Innovation

Commercial use of tools from the revolution in molecular biology contributed more than $350 billion to the US economy in 2012 by one estimate, with a 10 to 15 per cent annual growth rate (Carlson 2014). If the U.S. experience is a guide for future growth in the field world wide, each commercial sector of the biosciences – industrial biotechnology (including bioenergy), genetically modified plant crops, and biological drugs – will contribute roughly a third to overall output. Products arising from molecular biology constitute a growing share of the global economy with each passing year as technologies evolve, production processes improve, and markets expand. In recent years industrial biotechnology has been the fastest growing biotechnology sector (Carlson 2014). That bodes well for mitigation of greenhouse gas emissions because bio-based products in the materials and chemicals sectors (as well as next-generation biofuels) have a much smaller environmental footprint than products such as petroleum-based plastics and petro-chemicals (OECD 2011).

Global investment in biotechnology has enjoyed solid growth since 2012, and 2014 was a banner year. *BioCentury*'s Walter Yang compared 2014 to 2013 (Yang 2015):

- Biotechnology stock indices advanced at an average of 31 per cent.
- The industry raised nearly $55 billion globally, up by 47 per cent.
- 112 initial public offerings (IPOs) raised a record total of $9 billion, up from 60 IPOs that raised nearly $4 billion.
- The number of IPOs in Asia-Pacific was 74 compared to 42; these IPOs raised $691 million over $309 million.
- The private sector raised a record $9 billion, doubling the amount from 2013. Asia-Pacific accounted for $274 million of private sector investment, up by 20 per cent.

Because of high drug development costs, estimated to average $2.5 billion for an approved prescription drug in the U.S. (Mullard 2014), global investment in the biotechnology field remains highly concentrated in the biopharmaceutical sector. The biopharmaceutical industry, estimated to be a $150 - $200 billion global market[10], was founded on advances in molecular biology in the 1970s. Newer biological technologies like genomics, synthetic biology, and regenerative medicine are positioned where molecular biology was four decades ago, in the early stages of attracting significant investment (Woodford 2015). Some of these technologies are geo-technologies involving automated bioanalytical and biosynthesis instruments, systems, and devices often linked to data networks.[11]

The biosciences have many new cutting-edge tools from genomics and bioinformatics, cellular technologies including stem cells, and synthetic biology, with assists from nanotechnology and automation. These tools make it possible to sequence and synthesize DNA at an industrial scale, edit genes precisely, control the growth and differentiation of cells and print them in three-dimensional constructs (bioprinting). They also make it possible to create microbial factories that produce medicines, renewable fuels and chemicals, and biodegradable materials.

As noted above, growth in the industrial biotechnology sector – for cleaner and greener technology, chemicals, materials, and fuels – is vital for severing the link between economic growth and CO_2 emissions (OECD 2011; BIO 2013). We are at the dawn of the industrial enzymes era that is putting existing enzymes to novel uses and creating novel enzymes to catalyse an expanding array of biochemical reactions. Asia accounts for more than one-third of the multi-billion dollar industrial enzymes export market, with China accounting for 20 per cent (Binod *et al*. 2013). The potential for synthetic biology and metabolic engineering to accelerate growth in the design and manufacture of industrial enzymes and bio-based products is just beginning to be realised.

Genetic networks and biosynthetic pathways in microorganisms are being adapted, reorganised and recreated to manufacture biopolymers, bioacrylics, butanol, bio-isoprene for tires, surfactants, and 1,3-propanediol (PDO), a production platform for solvents, adhesives, resins, detergents, and cosmetics. The integration of software and wetware in synthetic biology (synbio) should dramatically shorten the innovation cycle for making new bio-based products (OECD 2014). Bioremediation has been employing microorganisms to reduce heavy metal contaminants in soil and water for several decades but with less than optimal utility. Synbio coupled with genomics, biosensing and ecosystem profiling constitute potentially invaluable tools for designing novel and much more effective environmental remediation systems for soil and water contamination, a significant problem for fast-growing countries in East and South Asia (Wong 2013; Banerjee and Sanyal 2011).

Genomics is opening a window on genetic alleles that enable food crops including wheat, rice, and maize (corn), Earth's major cereal crops, to adapt to a changing climate. Their yield needs to grow by an estimated 70 per cent by mid-century to feed the projected nine billion people expected to then inhabit Earth (Kole 2013). Much of the overall population increase between now and 2050 is projected to take place in high-fertility countries, mainly in Africa but also countries with large populations such as India, Indonesia, Pakistan, the Philippines and the United States (UN 2013). The challenge of feeding nine billion people without further deforestation and environmental degradation has resurrected the specter of Malthusian limits. As *The Economist* concluded in a special report, "The 9-billion people question" in 2011, feeding the world in 2050 given the ecological constraints on land and climate change "of which agriculture is both cause and victim" will be hard. Business as usual will not do it (Parker 2011).

Some of the production benefits of agricultural biotechnology have been achieved for large seed market crops such as maize, soybean, and cotton but not for the vast majority of food crops owing to regulatory hurdles, public apprehension, and political activism (DeFrancesco 2013; Camacho *et al.* 2014). Yet even with the powerful tools of food crop bioscience – marker-assisted selection, targeted mutation-selection, genetic modification, and others – it is not clear that current crops can be pushed to produce as well as they do now at expected higher temperatures and with less water. Researchers studying yield trends of four key crops from 1961 to 2008 found that more than a quarter of maize, rice, wheat, and soybean cropland areas worldwide are stagnating or in production decline (Ray *et al.* 2012), a clear sign that yield trends are woefully insufficient to double crop production by 2050 (Ray *et al.* 2013).

The molecular biology toolbox is filled with the contributions of microbes, but perhaps no microbially derived tools are as potentially game-changing as the new engineered nucleases. These nucleases can be directed to make double-strand DNA breaks at specific recognition sites of the genome. The genome editing technologies – zinc finger nucleases (ZFN), transcription activator-like effector nucleases (TALENs), and the CRISPR-Cas nuclease system – give scientists the unprecedented power to remove or insert specific DNA sequences, in principle anywhere in the genome and through an efficient and reliable process. Words, sentences, paragraphs, indeed entire pages of the book of life can be rewritten or entirely removed. Precise genomic editing has been demonstrated in a number of crop plants including rice, wheat, and sorghum. "This technology promises to change the pace and course of agricultural research," wrote Jennifer Doudna and Emmanuelle Charpentier, inventors of the CRISPR-Cas9 genome editing system (Doudna and Charpentier 2014). Experiments show that precise genetic edits are passed to the succeeding generation of plants without new mutations or off-target editing, leading Doudna and Charpentier to conclude that such findings "suggest that modification of plant genomes to provide protection from disease and resistance to pests may be much easier than has been the case with other technologies." Synbio techniques for making multiple deletions, additions, and other edits to plant genomes stand out as a particularly important set of enabling technologies for instituting nitrogen fixation capability, improving nutrient content, and potentially enhancing photosynthetic efficiency (Lau *et al.* 2014; Rogers and Oldroyd 2014). The nearly 200 million tonnes of the nutrient fertilisers (nitrogen, phosphorous, and potash) used annually (113 million tonnes of nitrogen fertiliser) to meet the nutritional needs of the human population, particularly in East and South Asia, harm aquatic ecosystems, distort nature's biogeochemical cycles, and contribute to climate change.[12] The tools for fixing nitrogen in cereal crops through expression of a functional nitrogenase enzyme in cereal plants or through transferring to these plants the capability to form a symbiotic association with nitrogen-fixing bacteria appear to be on hand.

Conclusion: Brussels and Beijing: A Tale of Two Cities in an Anxious Age

Government decisions in two cities separated by a third of the earth's circumference help to illuminate the circuitous path ahead for bioscience, innovation, and ecosystems ecology. In late 2014, European Union political leaders in Brussels backed a plan to allow member nations to ban genetically modified (GM) crops on their soil even if the European Union approves them. In early 2015 the elected members of the European Parliament in Strasbourg, France voted by an overwhelming majority to allow member states to ban GM crops. They did so, *Nature Biotechnology* editorialised, "in the face of potential fines from the European Court and litigation from seed companies frustrated by foot-dragging and deadlock in European product authorizations" (NBT 2015). The ostensible justification for leaving the GM approval question with member states is subsidiarity, the principle that political decisions should be made at a local level if possible rather than made by a central authority. Since seeds and pollen do not recognise national borders, however, policymaking in high places and reality on the ground are likely to go their separate ways, resulting in genetic outcrossings and admixtures.

In leaving the decision to member states the European Parliament freed GM technology from "intense anti-GM lobbying at the heart of Europe" but may have paved the way for lengthy legal battles as each member country wrestles with the question of whether to move forward on GM crop approvals or ban GM crops entirely. Meanwhile, GM products approved by the European Food and Safety Authority, the EU regulatory body, are in limbo (NBT 2015). Only one GM crop – maize – is grown in Europe, mainly in Spain and Portugal (Lewis 2014). The "Frankenfood" movement has outpaced evidence-based rational analysis; culture has trumped science and entrepreneurship. On the question of GM crops, Western Europe, the innovative party in Pomeranz's "Great Divergence," is taking a distinctly different course from the one that changed the world two centuries ago.

As Brussels dithered and eventually punted, across the Eurasian landmass, in Beijing, the Chinese government exercised its central authority. It pledged more support for research on GM techniques, especially for crops. "After years of uncertainty, funding cuts and public arguments," wrote ecologist Qiang Wang of the Chinese Academy of Sciences in *Nature*, "the country's central government has issued a clear edict: China needs GM, and it will work to become a world leader in the development and application of the technology" (Wang 2014).

China sees the writing on the wall. Record Chinese imports of grain reflect dependency on others for the country to feed itself, an uncomfortable dependency illustrated by alleged Chinese theft of high-tech Western seed (Bunge 2015). To be self-sufficient, Wang observes, China must grow food for nearly one-fifth of the world's population with just 6 per cent of the world's fresh water and 7 per cent of the world's arable land. The near doubling of grain production in China between 1978 and 2013 was driven by a six-fold rise in the use of chemical fertilisers. China may be the global factory, but it is agriculture, not industry, that is the main source of the country's pollution. "GM technology has the potential to produce more food with less pollution," Wang says.

The Chinese government awarded key patents to Davis, California-based Arcadia Biosciences for its transgenic nitrogen-use efficiency technology, which has shown improved productivity of rice and wheat along with decreased fertiliser requirements in field trials (James 2013).

Arcadia Biosciences' GM rice has also produced strong yields under drought stress, based on field trials in India (Anderson 2015). China is expected to experience more frequent and more severe droughts with global warming. "The area of crops impacted and affected by droughts throughout the country has been increasing for several decades," say Chinese climate scientists. "Since the beginning of the 21st century, regional droughts happened more frequently wreaking major havoc" (Ge *et al*. 2014).

China imports substantial quantities of GM maize (corn) and soybeans but grows only GM cotton, papaya and popular trees that serve as windbreaks in the windy north. Following a speech by Chinese president Xi Jinping that backed China's development of genetically modified crops as a means of strengthening food security, agriculture minister Han Changbin followed up with measures for promoting GM food to the public (Hornby 2014). Beijing is counting on Chinese scientists, most of whom directly or indirectly work for the government, to educate a skeptical public about the benefits of GM technology (Wang 2015). More than 13,000 Chinese scientists work in agbiotech, China's fastest growing biotech sector with $4 billion in annual government funding (Huang *et al.* 2012). The government's investment in agbiotech R&D is designed to "raise agricultural productivity and ensure national food security through novel GM technology." David Talbot in his article "China's GMO Stockpile" captures the spirit of China's determined effort:

> Exuberant and prone to charming bursts of laughter, Caixia Gao embodies the optimistic, energetic present of GMO research in China. Wearing a gray T-shirt emblazoned with 'Just Do It' in large pink letters, she leads a tour of her greenhouses at the State Key Lab of Plant Cell and Chromosome Engineering at the Institute of Genetics and Developmental Biology, part of the Chinese Academy of Sciences in Beijing. She's one of the world's leaders in using sophisticated gene-editing technologies, including those known as TALENs and CRISPR (Talbot 2014).

China was the first world civilisation to create a non-patrimonial, modern state, which it did nearly two millennia before the modern state made its debut in Europe (Fukuyama 2014). The Chinese have far more historical experience than any other people co-existing with centralised administration and bureaucracy. Beijing has been very successful in planning and developing large, technically demanding infrastructure projects, which are typically accomplished with public acquiescence if not public approval. Unlike most Chinese, Europeans are prepared to question science and scientists because of the power they can wield. “This could reflect the instinctive uneasiness that the average European would have with the concentration of power in few hands, something that the average Chinese might perhaps be less worried about” (Rerimassie *et al.* 2015).

China has cast its lot with evidence-based agricultural bioscience at a time of rapid growth in the country’s research and development and patent filings and when it is poised to become the world’s largest economy (if it isn’t already).[13] Beijing’s decision to embrace GM crop production plus the extraordinary tools now available to reengineer plant genomes set against the Western Europe’s generally hostile view of the technology makes Pomeranz’s “Great Divergence” appear slightly shopworn. The new “Great Divergence” may be the gulf between rapidly advancing science and public opinion. More than any other science – Big Bang physics, climate change, evolution, vaccine safety – the American public is doubtful about GM foods and whether they are safe despite nearly three decades of testing.[14] In a Pew Research poll, 37 per cent of American adults versus 88 per cent of American scientists surveyed considered GM foods generally safe to eat, a 51 point gap (Pew Research Center 2015).

China may not have had easily accessible coalfields or colonial resources as Britain possessed to fuel its industrial revolution, but today’s ecological and natural resource limitations and Malthusian pressures are coming into play in China and indeed throughout East and South Asia. When coal, steam, and mechanisation opened up vast new technical possibilities, “western Europeans (especially in England) were in a unique position to capitalise on them,” Pomeranz wrote in *The Great Divergence*. “Vast untapped New World resources (and underground resources) still lay before them, essentially abolishing the land constraint.” Once again vast new technical possibilities are opening up. Once again land is constrained. Dealing successfully with these possibilities and constraints in light of public misgivings about science would constitute a momentous achievement for twenty-first century political economy.

Endnotes

[1] See also McNeill (2000), Fernandez-Armesto (2001) and Marks (2015).

[2] Pomeranz borrows the term "biological old regime" from Fernand Braudel (1992). Braudel's chapter subtitle is: *1400-1800: A Long-lasting Biological Ancien Régime. He writes: "These then are the facts that go to make up the biological ancien régime we are discussing: the number of deaths roughly equivalent to the number of births; very high infant mortality, famine; chronic under-nourishment; and formidable epidemics."*

[3] *Dabla-Norris et al. (2013) at the International Monetary Fund note that* the overall picture of growth among developing economies since the 1990s "masks an uneven pace of convergence across regions and countries, reflecting considerable heterogeneity in growth drivers." In developing Asia, they write, rapid growth predated the 1990s, "with *capital deepening* playing a more important role in the catch-up processes of the faster-growing countries compared with other regions, fostered, in part, by high domestic savings rates in East Asia…."

[4] For two centuries following publication of Adam Smith's *The Wealth of Nations*, land, labour, and capital were the compelling and unchallenged inputs that economists took into account in their calculations for predicting economic output. Not until the second half of the twentieth century did that tried-and-true construct begin to give way when Massachusetts Institute of Technology economist and Nobel Laureate Robert Solow introduced the idea of technological progress as an additional factor in economic output, the "Solow residual."

[5] The National Institutes of Health awarded $5 million to each of four grantees in fiscal year 2013 under the Genomic Sequencing and Newborn Screening Disorders research program, from http://www.nih.gov/news/health/sep2013/nhgri-04.htm.

[6] GenBank.gov

[7] Nationalgenebank.org

[8] Earthmicrobiome.org

[9] For background information about Joseph Needham and his *Science and Civilization in China* series visit the website of the Needham Research Institute: http://www.nri.org.uk/.

[10] Biopharmaceutical drugs or biologics now constitute approximately 20 per cent of the global pharmaceutical market with an annual growth rate of 8 per cent, double that of conventional pharmaceuticals. See Otto, Santagostino and Schrader (2014). India aspires to be a leader in the emerging biosimilars industry as it is in the generic drug industry. See Ail (2014).

[11] See a world map of high-throughput sequencers at Omicsmaps.com.

[12] For the amount of fertiliser nutrients (nitrogen, phosphorous, and potash) used annually, see FAO report *World Fertilizer Trends and Outlook to 2018*. The FAO writes: "The dependence of *East Asia* on nitrogen imports is expected to continue." For a general discussion of the next steps to engineer crop plants that fix nitrogen, see Beatty and Good (2011). For the effects of nitrogen-based fertiliser on the nitrogen cycle, see Fields (2004) and Ward (2012). For a discussion on the impact of nitrogen fertiliser use on the environment and climate, see Foley *et al.* (2011).

[13] Comparative data showing national research and development as a percentage of GDP is available in Chapter 4: "Research and Development: National Trends and International Comparisons" in *Science and Engineering Indicators 2014*, National Science Foundation, Washington, DC. Available at: http://www.nsf.gov/statistics/seind14/index.cfm/chapter-4/c4h.htm Among the highlights: "The pace of real growth over the past 10 years in China's overall R&D remains exceptionally high at about 18% annually, adjusted for inflation."

For China’s surge in patent applications, see “US and China Drive International Patent Filing Growth in Record-Setting Year.” World Intellectual Property Organization (WIPO), Geneva, 13 March 2014. Available at: http://www.wipo.int. On the question of China’s economy vis-à-vis that of the U.S., see “9 Facts on China’s Economy Overtaking the United States”, *The Globalist*, 6 March 2015. Available at: http://www.theglobalist.com.

[14] For a history of GM crop and food development, see Chapter 1 in Newton (2014). A scientific literature analysis of 700 papers on the subject of GM crops food/feed safety issues published between 2002 and 2012 show that **“**GM crops have been extensively evaluated for potential risks and that genetic modification technologies based on recombinant DNA do not carry a greater risk than other types of genetic modification.” (Sanchez 2015).

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