Some closing thoughts

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Throughout this book we have seen examples of trade-offs and seemingly irreconcilable differences confronting those concerned with global prosperity and food security. In some cases these differences shrink as technology has provided a path around heretofore-major obstacles. The rapid and widespread adoption of cell phones has enabled mobile banking and microfinance to be taken up by even the smallest producers. Access to credit and competitive prices for their products empower even small farmers in a way few thought possible before the turn of the 21st century. Blockchain technology is almost certain to disrupt and, at least from farmer and consumer perspectives, positively transform agricultural production and markets in developing countries. Likewise, scientific, technical and policy advances have effectively overcome what seemed at the time to be insurmountable obstacles. Not only were the genetic innovations required for adoption of stress-tolerant rice successful, major changes in national and regional seed policy provided the means for these varieties to be rapidly disseminated in South Asia. Even more encouraging are the examples of current and impending breakthroughs that promise to further improve nutritional composition of staples, the productivity of agriculture and its compatibility with a healthy environment.

The profound increase in how information is generated and exchanged directly impacts the rate of scientific advances as new findings flow into the global scientific community in near real-time. The pace of scientific advances is increasing in a classic positive feedback process. The sheer volume of discovery and the demand to assimilate new knowledge and perspectives, combined with demographic and economic trends, are causing massive change in our societies. Can the same positive feedback system that drives technological innovation operate with policy innovation? Or, are the rates of change in technology so divergent from the realities of policy development that they are condemned to be increasingly out of synchrony?

Indeed, as this book was being finalised, the Court of the European Justice of the European Union, the highest court in the European Union, ruled that gene editing using mutagenesis techniques, such as CRISPR–Cas9, is subject to the same rules as genetically modified organisms in which foreign DNA is inserted and remains in plants that ultimately will be grown in the field. The ruling asserts that the precise mutagenesis technique, leaving no foreign DNA in the final product, must be regulated. However, random genome-wide mutagenesis that has been used in plant breeding for decades need not be regulated,[1] based on the 2001 EU Directive (2001/18). The puzzling ruling that a random mutation process would be considered safer than a targeted mutagenesis reveals the underlying rigidity of policies within the existing legal framework. The difficulty of updating such directives to reflect rapidly changing science simply highlights the kinds of issues that will become more common as technological advances outpace policy revision mechanisms.

Science is in many ways a free-wheeling process in which ideas and hypotheses are subjected to a brutal, transparent process of validation and refinement. The scientific method is used to eliminate as much as possible social values, norms and biases from the assessment of the results of inquiry. The criterion for success is simply reproducibility of experimental results by independent researchers. Although the scientific method sets rigorous standards for testing hypotheses, there certainly can be resistance to change. It is not a trivial undertaking to challenge well-established scientific dogma. But, within the scientific community it is understood that even the most tested and accepted theoretical frameworks are only valid within the conditions under which they were developed. Their application domains may end up being circumscribed as new knowledge and understanding emerges. Newtonian mechanics, for example, work well within our macroscopic world – and for centuries were viewed as absolute – but have been supplanted by quantum mechanics in the subatomic world.

There is good reason to believe that many of the technical or biophysical challenges that face us can be resolved with technical or biophysical solutions. This is not to say that these solutions will be perfect, and no doubt they will contain their own next-generation problems. Indeed, the Haber–Bosch process highlighted at the outset of this volume is a case in point. Transforming atmospheric nitrogen into ammonia is an important source of greenhouse gas emissions: a concern unappreciated when the process was developed.[2] However, recent advances in using renewable energy sources to fuel the process should bring emissions down, and successful development of reverse fuel cells could completely eliminate carbon from the ammonia production cycle (Service 2018).

While the future of technological innovation may be bright, how will society deal with the thorny questions of winners and losers as some technologies prove to be disruptive? Advances in genetics will enable us to develop far healthier foods, and advances in agricultural practices and remote sensing will without doubt continue to result in more-efficient food production systems. Consumers, increasingly urban for sure, will be primary beneficiaries of these advances. But, how will benefits be apportioned among consumers, farmers and companies developing and selling the products of innovation?

Of particular concern is from where the innovation will come that is necessary for the development of future agricultural technologies upon which future food security depends. It is true that agricultural science benefits greatly from investments made in other areas, and for reasons very different from assuring food security. So, the amount of direct investment in agricultural research may be an imperfect proxy for overall availability of research findings to the agricultural community. Medical research was the main driver for most of the techniques that plant sciences use for understanding plant genetics and managing very large datasets. Military applications justified the development of many of the satellites and imaging technologies used for Earth imaging and geographical positioning systems. These are critical enabling technologies for many innovations from plant breeding to forecasting crop production and disaster relief. But, can society afford to depend on spillover technologies as the major source of innovation in agriculture?

Regardless of whether or not agriculture was the primary intended beneficiary, it is clear that major public sector investment made transformative technologies possible. Furthermore, additional public sector investments were needed to translate these innovations into forms that could then be taken up by the private sector.[3] Adapting innovations from more-developed agricultural economies and creating new ones for developing countries was an important driver for the creation of the CGIAR (www.cgiar.org).[4] A further justification for maintaining a system of international agricultural research centres such as the

CGIAR was the creation of international or global public goods. These are technologies or knowledge that are freely available to all and whose value to others is not diminished by their use by one individual, entity or country. These goods could be taken up and used to develop proprietary technologies by the private sector, while leaving the underlying technology available for others to use. In some ways this concept prepared the ground for the open source community in software and Creative Commons in publishing. It is true that the private sector plays an important role in taking innovations to farmers, even in many developing countries (Pardey *et al*. 2018). However, as several authors have pointed out in this book, public-sector-financed research is often the foundation for the private sector to create their commercial products and take them the 'last mile'. Gutting of investments in public sector agriculture research and extension had particularly severe consequences for Africa, as we have seen. Is current public sector investment sufficient to maintain the flow of technologies that the private sector relies upon to create useful products? Unfortunately the answer looks to be trending towards 'No'.

In recent decades, investments in R&D have declined in the wealthy countries where public investments in R&D were historically the largest, while middle-income countries such as China, Brazil and India are increasing their investments. Disturbingly, most lower income countries are falling further behind in their R&D investments (Pardey *et al*. 2018). Most striking is the deterioration in investment in international agricultural research. The CGIAR has seen major changes in support and scope over its history. Although its budget in constant dollars has remained relatively flat since the late 1970s, its mission has expanded to cover an ever-growing donor wish list to include natural resource management, climate change, equity and biodiversity, to name a few. Funding of CGIAR research programs and institutions is increasingly unreliable and very tightly linked to short-term projects. Unrestricted funding that all research programs need to explore new opportunities has nearly completely disappeared from the system. Most concerning is an increasingly complex CGIAR governance structure that seems to be incompatible with an agile institutional environment that fosters innovation. The CGIAR has historically been a source of agricultural international public goods and education of younger scientists in the poorer countries in the developing world. There is now a serious risk that, if the capacity of the CGIAR continues to dwindle, there will be no public sector alternative to meet these needs.

It is a common refrain that the private sector will take up the gap created by a shrinking public sector. But, as we have seen, the private sector will invest only where there is an attractive return on their investments. While reasonable from a shareholder's perspective, what becomes of the needs of farmers, crops and regions that are not commercially attractive? 'Orphaned crops' are orphans in part because there is little economic gain from investing in them. Extremely heavy regulation of some plant biotechnology means that only the largest companies can afford to take some bioengineered products to market, and straightforward business decisions dictate that only those crops with the very largest markets and economically engaged farmers are suitable for investment. The story of 'Golden Rice' is an illustration of the problems the public sector faces in trying to create and take a genetically engineered staple food crop to market.

If the CGIAR is no longer able to create the international public goods that are still needed, is it appropriate to consider creating an alternative model for creating these goods? Or does the global community leave the situation to reach an equilibrium where only the private sector and a few high- and middle-income countries determine what products are available, to whom and at what price? This would be a 'market solution' to the problem posed by declining public investment in agricultural research. Public investments in research and education, however, are made specifically to mitigate the cruelty of the market. Various national and international food security safety nets have been put in place over the last 50 years or so precisely to avoid the misery imposed by sudden spikes in food prices or local shortages that are the realities of 'market solutions'. Many, if not most, countries at the very least profess their desire to protect their most vulnerable people from hunger, demonstrating that society overall has decided that market solutions in such cases are not acceptable.

This brings us to the larger question of the proper relationship between science and policy. Although science strives to remove human values and expectations from its analytical framework, policies are developed to encode values into practice and to reconcile as much as possible competing and possibly conflicting values. Policy development is a messy and time-consuming process involving trade-offs and allowing space for economic and social shocks to be absorbed, understood and, hopefully, ameliorated. Is the accelerating change in technologies outstripping the capacity of human institutions to develop resilient policies that can be responsive to rapidly changing circumstances and understanding? The Court of European Justice ruling mentioned earlier is a current example of the growing disconnect between policy and technology.

Is scientifically generated knowledge simply a feedstock for policy makers? Are objectively determined facts only one small set of the mix that goes into policy discussions? How do we reconcile contradictions of cherished beliefs with new facts? Can we avoid an almost permanent state of cognitive dissonance?

The Asia perspective of yin and yang offers a useful perspective in sorting through what may appear to be irreconcilable conflicts in values or objectives. In Chinese philosophy seemingly contradictory forces, destruction and renewal, for example, are seen as essential dualities that make up the larger whole of reality.[5] Examining one without the context of the other can be very misleading and counter-productive. Describing and responding to dualities as 'either/or', rather than as 'and', can create conflict and lose–lose outcomes.

It is clear that unintended consequences of technological change are not predictable and that whether or not their impact is positive depends very much on one's perspectives, values and time frame. Applying the yin and yang perspectives to unintended consequences (commonly assumed to be negative) and unforeseen, or under appreciated, benefits, led me to the idea of 'convenient convergence'. Farmers living in marginal areas often suffer weather-related crops losses. Improvements in the genetics of their crops and in agronomic tools can improve productivity and ultimately transform marginally productive environments into reasonably productive ones. The immediate social return may not be great in the short and medium term. But improving crops for drought and flood tolerance in marginal environments will also create new knowledge, techniques and crops more suited to environmental stresses most likely to increase as a result of climate change. It is a convenient convergence of interests, indeed, when local solutions to problems that plague the very poor living in marginal environments turn out to be useful globally as we confront our changing climate.

Some trade-offs are unavoidable, but are not necessarily in outright conflict. Conservation of our environment need not be incompatible with the intensive agriculture needed to support human populations. Indeed, maximising agricultural output from the smallest land area may well be one of the best ways to preserve natural areas. Efficient farming allows for lower prices: a benefit to consumers. But these prices can be ruinous for small, inefficient, farmers on marginal land. Farming in marginal areas may provide the meagre livelihood for very poor farmers, and some have argued that preserving these ways of life preserves an important part of our broader cultural heritage as humans. But, what is the cost to society of preserving these communities? What is the impact of, for example, subsistence, slash and burn agriculture on the environment and biodiversity if rural populations grow? What say do people living in those communities have? Will farmers on marginal lands stay on their land if the price they receive for their crops is insufficient? Should poor urban consumers be asked to pay higher prices to subsidise small farmers on marginal lands? The rapid migration to cities that is taking place worldwide is strong empirical evidence that farmers will leave the countryside if urban life appears to offer more opportunity.

It is not surprising that a book looking at the nexus among science, technology and public policy should end with more questions than it started with. The nature of successful research and discovery is that in the process of answering one question more questions are raised and in the process of answering these our understanding grows. This feedback loop (again!) was seen in virtually every chapter of this book. So, the questions raised here at the close of the book may be indications that we have achieved some success.

In some important ways, the future of food security for most of the world's people will depend on how we strike the balance between public and private interests. Public investments over the last 150 years have created much of the knowledge base from which the private sector generates goods and services. Society benefits and the private sector profits under optimum circumstances. Public policies dictate to some degree how, when, where and who adopts new technologies. When society absorbs the risks and costs of developing enabling technologies, how far do society's rights extend to impose guidelines on how technologies are used and benefits apportioned? The relevance of these questions reaches into most aspects of modern life. But none of these considerations can be more important than their impact on the reliability and availability of our global food supply.

Endnotes

1 https://curia.europa.eu/jcms/upload/docs/application/pdf/2018-07/cp180111en.pdf.

2 By the early 19th century scientists had determined that common atmospheric gasses such as water vapour and CO_2 could trap heat in the atmosphere. At around the time Haber first developed the atmospheric nitrogen-to-ammonia process, the Swedish scientist Svante Arrhenius calculated that global temperatures could rise as a result of increases in atmospheric CO_2 concentrations from human activity. But, based on estimated CO_2 production rates at the turn of the 20th century this would take thousands of years (see: https://history.aip.org/climate/co2.htm).

3 The tension between public versus private sector investments and benefit accrual has been a divisive issue throughout my career. Often lost in the arguments around how farmers benefit is that farmers are firmly in the private sector.

4 While there are a number of vary large, sophisticated public national agricultural research organisations in the world, the national institutions have a mandate to further their national interests. The CGIAR was created to fill a public international research void.

5 The Hindu concepts of yoni and linga presents a similar duality and may share common roots with the concept of yin and yang (https://www.sanskritimagazine.com/indian-religions/hinduism/yin-yang-originated-india-hindu-connection/).

Reference

Pardey P, Alston J, Chan-Kang C, Hurley T, Andrade R, Dehmer S, *et al.* (2018) The shifting structure of agricultural R&D: worldwide investment patterns and payoffs. In *From Agriscience to Agribusiness. Innovation, Technology, and Knowledge Management*. (Eds N Kalaitzandonakes, E Carayannis, E Grigoroudis and S Rozakis) pp. 13–39. Springer, Cham, Switzerland.

Service R (2018) Liquid sunshine. *Science* **361**, 20–123.