1 Introduction to agriculture, biotechnology and development

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1 INTRODUCTION

Evidence is playing a greater and more conspicuous role in the shaping and management of public and private organizations and the rules that govern them. Decision-makers rely on evidence and must account for its use, but the processes for creating, normalizing and disseminating knowledge, as well as the standards for the evidence itself, are widely debated, discussed and documented. Apart from the theories and typologies of evidence generation and evaluation, one crucial variable underpinning and defining effective uptake and use of new knowledge is often missing: timing. In the context of emerging technologies where the knowledge base is incomplete, the timing of knowledge generation and use can determine the fate of technologies. This is especially true in the dialogue about when, where and how society should adapt, adopt and use new science-based inventions in the global agri-food system. The emergence of biotechnology in the global system has triggered a broad range of individuals and groups asserting that the technology is, or is not, appropriate to the context and needs of global agriculture and development. Careful consideration of the quality and provenance of evidence will always matter, but so too does the vital question of when is the best time to disseminate knowledge, especially as it relates to innovative concepts and products?

While every case of agri-food biotechnology innovation is different, some general rules about when and how to disseminate information apply. For example, knowledge acquired in the early years of a new technology's development, testing and uptake should, for a variety of reasons, be carefully documented and disseminated. Ultimately, this evidence will contribute to a complete story of the benefits and risks of the technology. In some instances, this may be at the first point of commercialization (what economists might call the *ex-ante* evaluation); at other times it may follow a lengthy period of sustained adoption (what economists call *ex-post* evaluation). In the context of agriculture, biotechnology and development, in 2013 both forms of evaluation exist. Readily available is extensive, detailed evidence of the impacts and effects of a few first generation technological adoptions on the actors, the debates, the economy and society. Less readily available are experiences supporting estimates of the impact of second and third generations of technologies and products, many of which might fundamentally change the structure and function of the global agri-food system.

Knowledge about iterative and transformative technologies, such as the recent technological changes in agriculture, accumulates incrementally over many years. Articles in the early to mid-1980s described the process of how one might genetically transform plants. These scientific publications have since provided more information and greater details about how to insert or activate new traits into plants. By the mid to late 1990s new articles

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began to appear that attempted to estimate the effects of this technology on consumers, producers and industry, both in developed and developing nations. This was matched by a flurry of work on consumer responses, intellectual property, regulatory frameworks, international trade impacts, biosafety assessments, adoption benefits and many other topics.

The application of biotechnology to agriculture has precipitated, if not the largest change in the history of agriculture, certainly the largest change since the move to mechanized agriculture. Responses to this innovation span a wide spectrum of applications and impacts. Much knowledge about the state of agri-food technology and its socio-economic impact on global agriculture, biotechnology and development has accumulated over the last quarter century of production history. Specific studies on the effect of agricultural biotechnology now provide a rich history and offer grounded thoughts on the future for the technology in this sector. The experiences and impacts of agricultural biotechnology (agbiotech) provide a unique perspective on how an innovation is able to provide global benefits in the face of some of the most hostile responses to commercialization experienced in recent memory. As this knowledge base has grown, drawing from an increasingly diverse set of sources, the timing is opportune for a handbook that gathers together the evidence on the main issues in agbiotech.

2 OBJECTIVES OF THE *HANDBOOK*

This book provides the reader with a diverse, but concentrated, perspective of the global application of biotechnology to plant agriculture. Readers will be able to gain rich insights into specific aspects of agbiotech (that is, impacts of genetically modified traits in an array of products, ranging from such large-area crops as corn and soybeans to niche products like papaya), and will also be provided with an assessment of the overarching structure that governs the trade and regulation of agbiotech processes (that is the role of national and international governance systems, such as the United States and European Union regulatory process and the World Trade Organization). These perspectives provide an evidence base for the reader to compare and contrast the results within the different applications. The book offers the reader detailed evidence of both the products and the processes that are part of, and important to, agbiotech. Readers will gain new insights into why agbiotech has been more successful in some geographic locations than others and why some products have been more successful than others and what this says about both the technology and its application to agriculture and the broader question of technology as a part of the development agenda.

3 THE ORGANIZING HEURISTICS FOR THE VOLUME

To realize the objectives of the book, the editors have applied three interrelated, three-pronged approaches to assessing the relationships between agriculture, biotechnology and development. In the first of the approaches, which might be labelled the 'epistemic' approach, the editors drew on previous work about the codification and organization of knowledge in an effort to lay the foundation for contributors to sort between: (a)

what is accepted or ‘Kuhnian’ normal science; (b) what is the focus of current research, where theory, methods and evidence are being advanced and tested; and (c) speculative pursuits, where standard research practices have yet to emerge. For the second approach, the editors adopted Elinor Ostrom’s institutional analysis and decision (IAD) framework as the superstructure for the *Handbook*. This framework supports rigorous analysis of: (a) the exogenous variables (that is, the actors); (b) the action arenas (that is, issues and decision points); and (c) the outcomes. The IAD is a useful organizing framework for categorizing the chapters of the *Handbook* into somewhat discrete categories. As a third approach, the chapter authors were asked to structure their contributions by self-consciously considering how they use: (a) established analytical or normative theories and models; (b) existing methods; and (c) standard or experimental metrics. The models–methods–metrics approach was encouraged as a way for authors to reflect on relationships that could be articulated in the IAD framework, and to speculate on knowledge gaps and research opportunities, thereby integrating the epistemic approach into their chapter. Combining these three approaches helps to give individual chapters, parts and the entire *Handbook* an integrated structure that bridges different sources of knowledge, institutional settings and dynamics and the tools and techniques used to understand the many facets of agbiotech. In the following three sections the approaches are described more fully.

3.1 Knowledge Framing, Priority Setting and Triage

Because this *Handbook* is a compendium of knowledge drawn from many complex and overlapping systems, it is important to specify the grounding criteria used to separate the grains of interest from the large volume of chaff. Four criteria were used. The first is straightforwardly epistemic. For any given question about agbiotech, a matrix can be constructed in which theory and evidence relevant to the question comprise the axis, and each axis is divided into ‘known’ theory or evidence and ‘unknown’ theory or evidence. Authors were asked to consider their topic in light of the ‘known evidence and known theory’, the inverted pair of ‘unknown–known’ theory and evidence, and cases where both theory and evidence are unknown but may be under discussion. This approach helps to categorize some questions as ‘normal research’ questions, in the sense defined by Kuhn (1970); other questions require future research, as uncertainties dominate.

Second, any investigation of knowledge must start with some concept of how ‘deep’ to go with a topic. Authors in this *Handbook* have been asked to address specifically both the ‘depth’ and the ‘breadth’ of the knowledge they surveyed. Some chapters, such as those examining the impact of specific technologies, are inherently fine-grained analyses. Others, such as the general operation of the regulatory or trade system, are more coarse-grained. Similar levels of granularity have been imposed within each of the three parts of the book, but between parts, divergence has been allowed. One might look at parts I, II and III as moving from coarse to medium to fine granularity, as the scale, scope and impact of the technology is increasingly delimited from the exogenous environment it engages with, to the adaptations in the action arenas and finally into specific applications in specific markets.

A third consideration is the ‘stopping rule’ used to circumscribe the range of topics considered in this *Handbook*. In the first instance, the basic topic – biotechnology

applications in plant agriculture and its impact on development – narrows the range of considerations. At the chapter level, authors have been directed to focus on their core topic and only secondarily to address overlapping considerations considered in other chapters. Thus circumscribed, this *Handbook* does not explore in depth many worthy but increasingly peripheral issues where ‘green’ agbiotech intersects with ‘red’ (medical), ‘blue’ (marine), and ‘white’ (industrial) biotechnology. These points of intersection could themselves comprise a lengthy and interesting *Handbook* in coming years.

Fourth, chapter authors were asked to differentiate between the iterative and transformative effects of the technology. Iterative change usually involves marginal improvements, resulting in technologies and products that substitute for, or complement, existing technologies. Iterative change is relatively modest and short-lived, but is easily assimilated by existing regulatory systems, commercial actors and ultimately by citizens and consumers. In contrast, transformative change involves new technologies that generate a wide array of new production, consumption and political and social opportunities, consequently challenging accepted concepts, technologies, products and organizational structures. The impact on governance systems can be acute and enduring, and tends to precipitate discourse and conflict. While the rate, scale and scope of the change will vary depending on whether the technology involves small, iterative adjustments or poses large, transformative modifications, the challenge remains the same. Institutions need to respond and to adapt to the new circumstances (Phillips, 2007).

3.2 The Institutional Analysis and Development Framework¹

This *Handbook*, and many of its chapters, uses Ostrom’s (2005) institutional analysis and development (IAD) framework to structure the analysis of the theoretical and the institutional underpinnings of the complex system that has delivered a range of new technologies and products in the global agri-food system. The IAD framework helps to separate the nested layers of organizational environment, rules, actors and outcomes in governance systems. The framework focuses on more than just the organizations; it also directs how one might interpret interactions between and among actors and the institutional rules and norms that govern their exchanges, thereby offering insights into the behavioural underpinnings of many developments. Importantly, the IAD framework accepts that interactions can be simple or complex. While some critics are concerned that this adds to the already complex and dynamic picture of institutional analysis, applied consistently it can help resolve much of the complexity surrounding any given problem without resorting to the reductionist simplification of many other approaches.

The IAD framework is a systems approach to policy processes, specifically focusing on inputs, decision-makers, outputs, outcomes, evaluative criteria and feedback effects (Figure 1.1). Ostrom argues that any complex system can be viewed as being composed of subsystems (she calls them ‘holons’) that interact with an overarching system. Each subsystem ‘can be “dissected” into its constituent branches on which the holons represent the nodes of the tree, and the lines connecting them the channels of communication, control or transportation’ (Ostrom, 2005, p. 12). While this notion of nearly decomposable complex subsystems has been around since Simon (1955), the IAD framework advances the approach by more clearly articulating the constituent parts and offering a framing for understanding how the components integrate into the meta-system. The

Source: Ostrom (2005, p. 15).

Figure 1.1 Components of the IAD framework

approach highlights that many of the interactions within and across the subsystems occur simultaneously and at multiple levels. The IAD framework therefore provides analysts with the luxury of either analysing the system as a composite or of focusing on selected subsystems independently or jointly. This very flexibility highlights the importance of the exogenous variables, the action arenas and the rules and linkages between them.

One key analytical feature of the IAD framework is that it helps to frame and interrogate the possibilities of polycentric governance – ‘a system of governance in which authorities from overlapping jurisdictions (or centers of authority) interact to determine the conditions under which these authorities, as well as the citizens subject to these jurisdictional units, are authorized to act as well as the constraints put upon their activities for public purposes’ (McGinnis, 2011, p. 171). Most theories posit that knowledge-based economies, such as agbiotech, rely on polycentric systems of governance (for example Porter, 1990; Nelson, 1993; Lundvall, 1992; Leydesdorff and Etzkowitz, 1998). The IAD supports the analyses of these systems by targeting attention on the governing forces which exert influence on each subsystem and in turn on the overall system. In the context of research-based innovation systems, multi-sectoral and multi-functional polycentric governance dominate.

At its most basic level, the IAD framework consists of three elements: (1) exogenous variables; (2) an action arena; and (3) the interactions that generate outputs and outcomes. Ostrom defines exogenous variables to include biophysical or material conditions (for example the physical and biological constraints and challenges in different growing regions), attributes of community (for example the industrial structure and political systems governing agriculture) and rules (for example the overarching legal and institutional norms and practices that delimit choices). The action arena is composed of action situations and participants – variously defining problems, issues, policy areas and networks or communities of individuals and organizations. Stone (1989) asserts that action areas are not so much found as constructed through causal stories. Interactions between action arenas and exogenous variables determine the outputs and outcomes, which are evaluated using criteria adapted from external systems or developed explicitly for the

circumstances. Outcomes are continuously fed back onto the action arenas (and at times change the exogenous factors), which results in ongoing transformations in the system (either at the level of the holons or subsystems or at the comprehensive system level). In this way each of these variables are connected to each other, which leads to extensive learning-by-doing and change.

In applying Ostrom's IAD framework to the examination of biotechnology in the crops-based agri-food sector, authors of each chapter were asked to examine an exogenous variable (Part I), an action arena (Part II) or a set of interactions and outcomes (Part III). Each author was asked to apply appropriate knowledge filters to consider the models, methods and metrics people have used, or ought to use, to understand the role of biotechnology. In effect, they were tasked with examining a specific set of institutions, issue areas or applications, identifying the models and analytical methods that are commonly used to define and examine the action area (what Ostrom might call the evaluative criteria) and then to critically survey and assess the outcomes observed. This approach is meant to identify gaps in the theory, methods or evidence needed to fully understand the implications of this ongoing technological transformation.

3.3 Models, Models and Metrics

Authors of the chapters were also asked to examine critically all aspects of the known social and natural science associated with their topic. In this context, clearly delimited and articulated models, methods and metrics are important tools for understanding the dynamics between contexts, organizations and actors reflected in the IAD framework. Because of the plurality of types and uses of models, methods and metrics, authors were encouraged to be explicit about the tools that they were using. For example various types of models can be used to represent the causal relationships in a system, and given the diversity of the actors, issues and applications, there are inevitably many facets of a system that can be represented. While this diversity adds significant explanatory power, it often is at the root of disagreements and disputes. While resolving these disagreements and disputes is not an appropriate task for a *Handbook*, this *Handbook* offers a compendium of a wide range of models that appeal to and bridge theoretical concepts from sociology, psychology, political science, policy and economics.

Models of a system rely on underlying methods to construct and validate them. Many disciplines and authors approach the validation of models inductively, with micro-level detail filling in the gaps of the theory and conforming to the implied structure, without explicitly testing the models in a scientific manner. In short, much of the work takes the theory as given and then applies it to estimate the impacts implied by the theory. Other work is more deductive in nature, using theory to derive refutable, testable hypotheses. Both methods have their place, but it is vitally important to know which is being undertaken. Standard performance indicators and conventional modelling can deliver useful information about how effectively closed-system technical problems have been solved, but they may be less effective in explaining how science and technology perform in an unbounded social context.

With respect to metrics, authors were asked to summarize and assess metrics that comprise the evidence base used in decision-making about agbiotech innovation. In some cases metrics refer to qualitative or expert judgement; in other cases, empirical

study is required. It is important to document data collection methods, whether involving primary or secondary data. The provenance of data can often have a major impact on general acceptance – data from statistical agencies, firms, community groups and farm-level or consumer surveys will have differing import. It is similarly important to disclose analytical methods; it is vital to know whether the focus is on economic, social, institutional or political factors, or whether the analysis is based on comparative static, partial equilibrium or computable general equilibrium approaches. Finally, every discipline has norms or standards to differentiate between data that is included or excluded; moreover, statistical practices and norms to validate statistics vary. It is important to keep in mind that methodological pitfalls exist in underlying fields such as econometrics (Leamer, 1983; McCluskey, 1983).

3.4 The Editorial Process

How this bespoke volume arose deserves comment. The editors, having considered how the IAD framework could be adapted to the context of agbiotech innovation, developed the basic structure of the book's sections and range of topics to be covered in each section. A list of potential authors was identified from the editors' networks and in some cases by researching the topic. Each author was asked to deliver a chapter of approximately 6000 words, including figures, tables and references; the goal was to produce the drafts within three months of commissioning. Many authors met the deadlines but exceeded the somewhat arbitrary word limit. In an attempt to assist readers to compare and to some extent contrast the diversity of biotechnology applications within agriculture, the chapters follow a standard set of basic headings. The value of this regular structure is twofold: first the authors had a clearer understanding of what they were to address within the body of their chapter; and second, the readers of the book have the ability to make assessments from one chapter to another. Authors were given a template that included a context-specific introduction, a survey of the theoretical models used, a review of the quantitative and qualitative methodological approaches used and a summary of the metrics, including the aggregate ranges of applications and impacts, the scale and scope of effects and the regional and distributional effects. Furthermore, the authors were asked to critically assess future theoretical developments, convergences, divergences and development of methods, and the shortcomings in data that need to be considered and remedied. Each chapter was reviewed by all of the editors, who provided detailed content and stylistic comments, suggestions and questions, which frequently initiated a second round of writing by the authors and review by the editors.

4 FINDINGS: THEMES, LESSONS AND GAPS

To frame the discussion in the many chapters of the *Handbook*, we invited Graham Brookes to provide an overview of the state of the industry in the period 1995–2010 for the first substantive chapter of the *Handbook* (Chapter 2). Although the first commercial genetically modified (GM) crop was planted in 1994 (tomatoes), 1996 was the first year in which a significant area of crops containing GM traits were planted (1.66 million hectares). Since then there has been a dramatic increase in plantings; by 2010/11, the global

planted area reached over 139 million hectares (and ISAAA estimates it rose to 170 m ha in 2012), equivalent to 71 per cent of the total utilized agricultural area of the European Union (James, 2013). GM traits have largely been adopted in four main crops – canola, corn, cotton and soybeans – although small areas of GM crops in sugar beet (adopted in the USA and Canada since 2008), papaya (in the USA since 1999 and China since 2008) and squash (in the USA since 2004) have also been planted. In 2012, 28 countries planted GM crops, more than half of which were developing nations. Six countries accounted for 94 per cent of total production: US, Brazil, Argentina, Canada, India and China (in declining order of area). Two traits dominate: herbicide-tolerant crops account for 65 per cent of the total GM area, while insect-resistant crops account for 35 per cent of global plantings. GM seeds account for 70 per cent of the global soybean acreage, 52 per cent for cotton, 26 per cent for corn and 20 per cent for canola. In those countries adopting GM varieties, GM seed market share has risen above 80 per cent. GM crops have also been pro-trade, in that adoption and production is concentrated in leading export nations. Brookes estimates that biotechnology producers account for between 72 per cent of cotton and 95 per cent of soybean global trade. These statistics suggest that there are *highly differentiated* actors, issues and impacts of the development and commercialization of biotechnology in plant agriculture.

4.1 Part I: Exogenous Variables: The Environment, Actors and Rules

The 18 chapters in this part examine a wide array of exogenous factors, external constraints and rules that govern the interactions of the key actors in the biotechnology, agriculture and development communities. The overriding message of these chapters is that there is a divergence in the various subsystems between those who are developers, adaptors, adopters and users and all the rest. Those with a stake in the effective, efficient and economically relevant use of biotechnology and agriculture are generally prepared to optimize their value. Those who are, or believe they are, disenfranchised from the technology, either because they do not own any of it, cannot productively use it or find it does not meet their social-economic interests, are actively engaged in opposing the technology. As with most controversial and contentious issues, the vast majority of actors in the agricultural and development communities are either silent bystanders or they are simply unaware or insufficiently invested to embroil themselves in disputes about the technology.

As befits a *Handbook* examining the current state of affairs in agbiotech, this part of the book offers a range of observations and analyses of how the lead developers and adopters and the pro-science institutions have accommodated and managed the introduction of new GM crops. The leading adopters, including Canada and the US (Bognar and Skogstad), Argentina and Brazil (Rhodes) and China (Karplus), and the partial or selective adopters, including India (Qaim), Oceania (Ludlow and Yorobe) and Africa (Thomson), have followed a common path. For the most part they have directed their public research capacities (Gray and Dayananda) towards advancing the science and applications and have at a minimum tolerated and in most cases partnered with private industry (Hobbs) to accelerate and focus the technology and its uses. These actors and jurisdictions have also proactively used existing regulatory authorities and structures and drawn on the longstanding policies and procedures in the global intellectual property system (Oguamanam), the multilateral risk analysis framework (Jackson) and the inter-

national trade system (Kerr) to effectively advance the technology in the agri-food setting (Bognar and Skogstad).

Juxtaposed against this juggernaut of investors, developers, promoters and users, there is a smaller but still significant group of sceptics, doubters and campaigners. While one might be tempted to point a finger at individual actors such as the European Union (Levidow), developing world non-adopters (Paarlberg and Falck-Zepeda), non-governmental organizations (NGOs) (Aerni) and consumer advocacy groups (Smyth and Castle), none of these actors alone appears to have enough power and scope to have much effect on the evolution of the sector. Together, however, they have effectively stalled, or at least slowed, the introduction of the technology into regions and markets that represent more than half of the global agri-food sector and about one third of the world's consumers.

Gray and Dayananda (Chapter 3) assert that the advent of biotechnology profoundly impacted agricultural research. Advances in molecular science vastly increased the scope of what is understood about crop, weed and pest genetics. Explosive growth of knowledge changed the possible, both in terms of the speed of genetic development and the scope of outcomes. But the potential was only realized when new intellectual property rights to genes, microbes, plants and varieties attracted the attention of the agri-chemical and pharmaceutical industry. Beginning in the mid-1980s, firms shifted focus and resources to exploit these new opportunities. Hobbs (Chapter 4) investigates the resulting periods of rapid investment, industry mergers and acquisitions and the ultimate globalization of research, development and commercialization. The end result is that we now have a highly concentrated, vertically and horizontally integrated, global industry. Somewhat paradoxically for such an innovative technology, the nature of the science and the regulatory challenges in both pro-biotech and other markets has worked to amplify the industrial concentration, to the point that there is little true entrepreneurial activity in the research and development (R&D) stages of the sector. Meanwhile most of the world's public research capacity grappled with how to respond. Gray and Dayananda (Chapter 3) note that while some public research organizations (PROs) withdrew in the face of the competition from multinational enterprise (MNE) research programmes (for example in the UK), others sought to partner with them to accelerate the development and adoption of the technology. They report that recently PROs are testing new models of engagement in order to sustain research on common pool problems such as genomics, elite germplasm and agronomy.

As these investments were proved up, they presented a challenge to regulators and the supply chain. The first and undoubtedly most important accommodations came in the United States. Bognar and Skogstad (Chapter 5) assert that American dominance in plant biotechnology can be attributed to explicit government policies to promote GM products. The promotional policies included strong protection for intellectual property rights and a generally permissive regulatory framework that does not discriminate against biotechnology. This approach, for the most part emulated in Canada and to a lesser extent in Mexico (which has a permissive but cautious approach), was guided by pursuit of competitiveness and economic gain.

This model of permissive and promotional regulation has been adapted and adopted across the globe, first in Latin America (Argentina and Brazil) and then successively in South Africa, China and most recently in India. While Alston, Kalaitzandonakes and

Kruse (Chapter 45) suggest that all adopters do not win equally, and some may barely hold their own, this bloc of adopting nations has held firm and is gaining adherents. James (2013) estimates that in 2012, at least 28 countries, representing the lion's share of the leading exporters for the four main commodities using GM varieties, have adapted, adopted, approved and commercialized at least one GM crop variety.

South America has been a strong adopter of GM soybeans. Rhodes (Chapter 6) asserts that Argentina, and more recently Brazil, have been generally pro-technology, pro-business and pro-international trade, with differences mostly based on the role of small, poor or landless farmers (especially in Brazil) and the role the multinational companies have played in the markets. One interesting recent development is that Brazil, which lagged in adoption due to erratic policy in the 1990s, has proactively cultivated relationships with the MNEs, while Argentina has lagged in locking in any significant MNE investments, at least partly due to its conflict-driven domestic politics and international policies.

A few African countries have been long-time incubators of biotechnology. Thomson (Chapter 7) examines the political economy of adoption of cotton in South Africa and Burkina Faso, maize/corn in South Africa and the ongoing research into cowpea, bananas, cassava and nutritionally enhanced crops in a variety of countries. Thomson concludes that while adoption has been modest, GM crops may soon dominate what is becoming a somewhat more prosperous region (*The Economist*, 2013).

China's role in agricultural biotechnology is indeterminate. While China developed and commercialized the world's first GM crop (herbicide-tolerant tobacco), it delayed making any irreversible decisions until the new millennium. Karplus (Chapter 8) asserts that China has been catching up and, in recent years, has emerged as a leader in crop biotechnology innovation. Karplus notes that China is a hotbed of socio-economic research and innovation, as scholars and practitioners are focused on understanding the transformations underway. This body of work may ultimately define what is examined and how research is undertaken in the many other industrializing and developing nations which have so far avoided making any explicit choices about this new technology.

Qaim (Chapter 9) examines the other enigma – India. While an early and engaged investor in biotechnology, India has engaged in a slow and conflict-ridden process of adoption. While the economic evidence suggests that Indian farmers benefit from new technologies by dramatically raising their cotton yields while containing their costs, there are persistent debates and invective directed at these developments. Farmer hardship and reports of related suicides have caught the attention of both Indians and international NGOs and the development community, generating a vociferous argument about the appropriateness of GM technology in this context.

Physically isolated from other nations and relatively free from external influence, a number of Oceania countries have responded to GM crops with unique, comprehensive GM regulatory schemes. Ludlow and Yorobe (Chapter 10) assert that distinctive regulatory schemes arise from many factors. Japan's absolute trade dependence and cultural sensitivities to change in key products has framed the measured and managed introduction of GM commodities through trade. Physical isolation of Australia and New Zealand has led to the development of highly distinctive flora and fauna and a history of harmful introduction of new species, and thus an overriding concern about the environmental impact of release of any new organisms. That isolation has also provided a modest

competitive marketing advantage as their products have been free from a range of pests common elsewhere and, in recent times, free of GM traits. No one wants to discard these benefits without full consideration of the trade-offs. Particularly in the case of New Zealand, the development of a strong organic farming sector provided a counterforce to GM crops. Finally, the Philippines are engaged in developing and testing new GM crops, but have had to wait for appropriate applications for the agro-industrial system.

The antithesis to the dominant model of adoption is the European Union, where a mix of agronomic realities, socio-economic considerations and political pressures has led to a multi-track policy, with some countries able and willing to adapt and use GM technologies (for example Spain), some opposed to them (for example Austria) and some for the most part waiting to see whether a GM or GM-free future offers the greatest potential benefits (for example France, Germany and the UK). Levidow (Chapter 11) notes that while the EU, especially the Commission and a few key member states (such as the UK), were early promoters of the technology, the technology became negatively associated with the hazards and apparent unsustainability of factory farming in the 1990s. Since then regulatory manipulations and prevarications have forestalled all but exploratory plantings – precaution rules in the face of uncertainties about the technology and its impacts. Since then, public and policy support has slipped, investment has declined and focus shifted to other priorities. The development pathway is now broken, with conflicts related to regulation, market access and consumer acceptance blocking widespread introduction of GM crops for the foreseeable future.

Paarlberg (Chapter 12) blames the EU and its policy and regulatory stance, both domestically and internationally, for stifling the more widespread adaption and adoption of GM crops in Africa, where he believes it could have major positive impacts. He asserts that the pattern of persistent regulatory blockage in the EU and uncertainty about market access for African exporters has discouraged both national scientists and international technology providers from making significant biotechnology investments to help farmers in Africa, which he laments. Given extensive channels of influence (for example bilateral assistance, multilateral technical assistance, European-based advocacy, interregional trade flows and cultural linkages), he fears that Africa will lose as a result of their inability to use this technology.

Falck-Zepeda (Chapter 13) offers a complementary story about non-adopters in Latin America, with similar pathways of influence having similar effects in a range of small to large markets that are unambiguously importers of technology. In those instances, a mix of concerns about protecting bio-diverse regions, challenges related to smallholders and the landless and concerns transmitted through environmental NGOs, donor agencies and Campesinos (rural farm workers) all have stalled development of scientific, regulatory and commercial capacity to adapt and adopt the technology. By contrast, Borroto (Chapter 14) offers quite a different picture through his investigation of Cuba and its efforts to nurture an indigenous, stand-alone, research-based industry. Perhaps most instructive, Cuba has demonstrated that lower-income developing countries can acquire and use the technology in ways that fit with their agro-ecological circumstances. The challenge is to get effective leadership and governance systems in place.

While problems and disputes often start at the local or national level in key countries, they quickly escalate to international forums. Jackson (Chapter 15) lays out the baseline multilateral risk analysis framework that virtually all countries adhere to and

which underpin dispute management in most forums. The difficulty, as Kerr (Chapter 16) points out, is that the corresponding dispute settlement processes in the multilateral trade system, embodied primarily in the World Trade Organization, various regional trade agreements (such as the NAFTA) and a new set of environmental agreements under the aegis of the Convention on Biological Diversity (especially the Cartagena Protocol on Biosafety, which attempts to manage the risks inherent in the first trans-boundary movements of living modified organisms) have gone some way to adapting the basic trade principles and processes to address the scientifically-based risks, but are unable to effectively address the socio-cultural concerns that motivate many critics. Despite more than two decades of negotiations to harmonize the rules and procedures related to trade in GM products, little has been accomplished. Kerr likens this effort to putting a square peg in a round hole, arguing that none of the international trade organizations are competent to deal with consumer and citizen protectionism – each of these organizations was designed to control industrial rent-seeking. Given that the trade rules cannot seem to bend to fit the new technology, many look to the other major international forums – a favourite next stop is the array of institutions engaged in managing ownership of intellectual property (IP). The WTO, through the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPs), has made international IP disputes actionable, which has raised the interest in how the International Union for the Protection of New Varieties of Plants (UPOV), the International Treaty on Plant Genetic Resources and the World Intellectual Property Organization (WIPO) can contribute to resolving disputes. Oguamanam (Chapter 17) offers an insight into the argumentation and strategies that developers, farmers, communities, activists and nation states have adopted to use these organizations.

The flies in the ointment, in many people's eyes, are the NGOs. On the one hand, there are consumer advocacy groups that report on, and attempt to foster, concerns about GMOs in foods. The main focus of consumer advocacy has been on implementing a set of mandatory disclosures through product labels, in an effort to advance 'consumer sovereignty'. The challenge has been that the evidence does not support the policy. When consumers are asked, only a small proportion are vehemently against GM foods; a larger portion of people express concerns that, as reported in Smyth and Castle (Chapter 18), can be traded off against other considerations, such as cost. Consumer concerns about GM foods have been on the wane, generally speaking. Whereas a decade ago heightened concern might have warranted changes in labelling regulations, Smyth and Castle conclude that given the shift in consumer attitudes, changes in labelling standards might not have the same warrant as they did years ago. One recent aspect of the labelling issue is further addressed in Chapter 30.

Aerni (Chapter 19) examines the 'uncompromising views' of environmental pressure groups towards the use of genetic modification in agriculture and its consequences for freedom of speech, dissenting views in academia, the empowerment of small-scale farmers and global sustainable development. He argues that environmentalists are not able to agree how to address sustainability problems effectively. One faction believes that technological and economic change is necessary to make the world more sustainable, which has led in many instances to entrepreneurial ventures and experimentation. An opposing faction of the environmental movement believes that new technologies are not able to be part of the solution, but part of the problem of sustainable development.

Drawing on lessons from nuclear technology, these groups focus on potentially irreversible effects of agbiotech on biological diversity. This perspective underlies the powerful, global network of NGOs and campaigners who target the technology wherever it is proposed for introduction, having drawn an immutable line in the sand. For the foreseeable future, Aerni sees little hope of convergence between those two perspectives. At present, they have embedded themselves in national and international policy processes and communities in ways that lead to a boisterous debate but little concrete action.

4.2 Part II: Action Arenas

Given the colourful cast of actors introduced in the first section – albeit necessarily a partial accounting – it is inevitable that there are a large number of action arenas. Each chapter in Part II examines a major arena, defined by different policy processes upstream (for example research management, technology transfer, intellectual property) or downstream (farmer adoption, commercial uptake and use, market effects and environmental effects). As one might expect from our preceding discussion of the actors, each action arena is contested; the adopters and non-adopters have differing views about what can and should be done with the relevant policy instruments. For the most part the developers, adopters and promoters dominated these arenas in earlier years, but their dominance now is contested. For the sake of simplicity, we have parsed the arenas into three main domains: upstream research management; the mixing of technology and markets; and downstream impacts and controversies.

Anticipating future research, or outcomes of current research, remains difficult, particularly as time horizons extend beyond any immediate set of projects. A number of authors in the *Handbook* were tasked with considering the agbiotech innovation pipeline, the transfer of technology from the pipeline to the users and the innovation processes themselves. Phillips (Chapter 20) offers a survey of the methods used for defining and interrogating the research pipeline, offering some insights into what these analyses say about the likely and prospective flows of inventions into the regulatory and commercial systems. In the first instance, this is important for investors seeking the best research prospects, and then for regulators who will have to respond to new GM crops. The message is somewhat troubling, as most capital and effort is directed to a handful of large-area crops and a small number of traits. New crops and new traits seem to be much lower priorities, a fact which will slow the value generation of agricultural biotechnology. Phillips cautions that these predictions are probably good for five years, after which there is little basis for prediction.

Instead of making predictions about the agbiotech pipeline, others consider the conditions under which clusters and innovation systems deliver new technologies, products and processes. Spielman, Zeng and Ma (Chapter 21) note that industry clusters have historically played a central role in economic growth and development, driven significantly by technology spillovers within geographically concentrated innovation systems. They posit that biotechnology clusters are emerging and concentrating around developing-country agriculture, which could accelerate the supply of new tools, products and value for small-scale, resource-poor farmers in the developing world. Their study of clusters in India, Kenya and China highlights the critical role for public investment, the need for innovation-friendly policies to support research and commercialization and the critical

role that context plays in success. The conclusion is that clusters are a powerful, but risky, development strategy.

Hennessey, Gupta and Kowalski (Chapter 22) investigate a number of case studies of technology transfer to developing countries, concluding that international tech-transfer is highly specialized and iterative, necessitating trained local human and institutional intermediaries. They note that the international movement of innovation is hampered by whatever proves to be the weakest link in the tech-transfer system (which can include laws and treaties or the owners and financiers involved in tech-transfer investment). In the case of agbiotech transfer to developing countries, the weakest links appear to be incomplete IPRs, inadequate tech-transfer competence, poor information access and weak management capacities. Their prescription is that developing countries will need to build some internal capacity and become full participants in the global system; right now they are mostly passive recipients.

Moving along the commercialization pathway, the next major step to consider is the set of structures and process that mix and match new technology with existing capacities and markets. This happens in the supply chain, on farms and in markets themselves. Schimmelpennig (Chapter 23) examines the structure and operation of the commercial supply chain in North America, ground zero for the new technology. He considers a range of exogenous variables such as the environment in Canada, Mexico and the US, the principal actors and the rules that have influence over them. He concluded that while the technology literature on agbiotech is extensive, several information gaps were uncovered that resulted from network failures in either industry structure, regulation or both. The clearest examples of these gaps were found to come from outside of North America, but these examples were chosen for illustrative purposes, not because information gaps did not exist in North America. The network gaps show large market impacts due to slow-moving or unavailable new agricultural biotechnologies, with related impacts on both producer and consumer well-being.

Farmers are a vital component in the commercialization pathway. Alexander (Chapter 24) notes that farmer choices are based on a mix of factors, including pecuniary rewards (for example yield gains, cost reductions due to saved inputs, higher profit, increased overall productivity and risk management) and non-pecuniary effects (for example simplicity or labour saving). But farmers are not all alike; many have different tolerances for risk and different production contexts that drive different valuation and adoption. Adopters win, but some more than others, based on their individual attributes; non-adopters lose unambiguously. Interestingly, none of the studies shows definitively that the benefits are biased towards larger or more intensive operations. In fact there are winners across the spectrum. While Alexander reports mostly on site-specific, comparative-static studies, Alston, Kalaitzandonakes and Kruse (Chapter 45) offer results from a new, partial equilibrium study that suggests that the effects may not be as straightforward as these single studies imply. What value individuals appear to gain from the farm-level perspective may be clawed away by the interrelationships between technologies, products and markets. Their chapter highlights the complexity of the technology treadmill.

A critical question often raised about the impact of biotechnology is whether GM crops can coexist with other crops. The concern is that if crops cannot be appropriately differentiated, then even small-scale adoptions could cannibalize otherwise valuable market segments. Beckmann, Soregaroli and Wesseler (Chapter 25) examine the

economic problem of coexistence, framing it in the context of three factors: consumer and farmer preferences for different production methods; the agro-ecological dynamics, which depend on the biology of the crops concerned and the agro-ecological environment in which they are released; and the broader institutional framework. They assert that while these key factors vary both nationally and internationally, coexistence can and has been achieved, wherever consumers are willing to pay. The cultivation of GM and non-GM crops at world level shows coexistence is possible. They conclude that small-scale studies using gene flow models show that commonly-used threshold levels of 0.9 per cent can be achieved without additional regulatory interventions. In general, whether or not coexistence will be possible depends on the threshold level and where the obligations are imposed. The resulting systems vary based on differing consumer preferences, while the distribution of cost and benefits differ according to how the regulations are structured.

One common concern is about corporate concentration in the biotechnology industry. Naseem and Nagarajan (Chapter 26) discuss whether the inputs industry has a greater degree of concentration due to agbiotech and, if so, what implications this has for market structure. The authors establish that consolidation has taken place in the agbiotech industry, but that cannot be solely attributed to the advent of agbiotech – it is commonplace to all maturing industries. Consolidation has primarily occurred within three sectors: seed development firms; technology firms; and chemical firms. In discussing the implications of this, the authors identify that the literature is inconclusive regarding impacts to innovation.

One of the biggest myths around new technology is that all of the benefits go to the inventor, or at least to the agent that commercializes the innovation. The reality is that even in the most monopolistic context, benefits are widely disseminated in the marketplace. Magnier, Kalaitzandonakes and Miller (Chapter 27) develop an innovative approach to estimating market power in industries with a large number of differentiated products. Their method yielded a worst-case scenario which offers an upper limit on the benefits that flow to inventors. They developed and fitted an econometric model and found that the upper bound on the corn seed mark-up is roughly 15 per cent, which they use to conclude that the amount of market power that was exercised in the US seed corn industry between 1997 and 2008 was rather modest. They also found that the life-cycle effect is concave over time, such that the initial price starts at a lower level, increases until the innovation's fourth year on the market, and then declines until the innovation is removed from the market or replaced by succeeding innovations. This provides empirical support for the notion that product life-cycle dynamics are important when examining patterns of price competition in industries with a large number of differentiated products.

Downstream, a range of controversies are bubbling along, variously commanding headline attention, resources and effort. Some are designed to optimize the operations of the system, while others are more about changing the underlying rules.

The evolution, structure and impact of what Eaton and Graff (Chapter 28) call 'the dynamic IP system' examines the past 30 years of litigation, legislation and treaty making, assesses the direct incentive effects of IPRs, the potential impact on competition and market structure and the theoretical and practical effects on public research, technology transfer, freedom to operate and international transfer. While some effects of the impact of IPRs on large-area GM crops are known, there is only limited evidence related

to small area crops and, perhaps more importantly, on the nature and direction that R&D programmes take in response to the evolving private rights for intellectual property.

Wolfenbarger, Carrière and Owen (Chapter 29) examine the environmental impacts of GM crops. Given that agriculture (defined as croplands and pasture) occupies about 38 per cent of the earth's terrestrial surface, the single largest global land use, the environmental effects of agriculture are widespread, with impacts both in production zones and surrounding areas. Which crops are produced, where they are produced and how they are produced determine the potential impacts on biodiversity and the ecological services upon which humans depend. The baseline for considering the impact of biotechnology is the well documented negative circumstances attributable to unsustainable practices of conventional and traditional agriculture. They conclude that herbicide-tolerant (HT) and insect-resistant (IR) crops have not exacerbated the negative impacts of agriculture on biodiversity and ecosystem services; rather, studies indicate that the use of GM crops is reducing the adverse impacts of agriculture by promoting conservation tillage and lower use of long-acting herbicides and highly toxic insecticides. To some extent, those gains are under constant threat. Pest resistance decreases the effectiveness of IR traits as insect species evolve resistance, and selective pressures due to widespread glyphosate use have led to at least 24 weed species evolving resistance. The agricultural practices that are adopted to minimize and manage the evolution of resistance will determine the future effectiveness of these GM crops and their related environmental impacts.

Consumers have responded to the uncertainty and controversy about GM crops in a variety of ways. The economic evidence suggests that consumers do not appear content to accept price signals alone to determine their purchases of GM foods. Many also want proactive, mandatory labelling of any GM content, in order to allow them to make choices based on other, intrinsic criteria. Huffman and McCluskey (Chapter 30) examined the role of labelling of GM foods. While all markets have some consumers expressing interest in differential labelling, only a subset of countries, mostly non-adopters (for example EU) and partial adopters (many Latin American and African countries), have implemented mandatory labelling through regulation. The other markets rely on voluntary labelling (enforced by tort and fraud laws) or standards-based labels (for example Canada with its labelling standard). While the labelling issue has quieted recently, the evidence presented by Huffman and McCluskey suggests that there is no reason to assume it will go away soon.

In the face of endemic food shortages in parts of Africa and Asia and increasing price volatility caused by mismatches in supply and demand and speculation on the market, the global policy community has global food security clearly in its sights. Agriculture was elevated to near the top of the agenda of world leaders in 2008–12 with strong, affirmative positions taken by leaders meeting at the G8, G20, UN, OECD and other multilateral forums. Juma, Conceição and Levine (Chapter 31) present a strong argument that the application of new technologies has played a critical role in past efforts to reduce food insecurity and will need to do so again. They point out that food insecurity is a range of mismatches between supply and demand in the market which leads to undernourishment, chronic malnourishment due to incomplete diets and instability in local food systems due to agronomic challenges. Biotechnology can help to remedy all three problems. They caution, however, that solving world hunger requires more than just producing more food. Strong institutional frameworks will be needed to strengthen public oversight and

transparency and empower small-scale producers and consumers alike. Inclusive processes of technology development, adaptation and adoption will ensure that benefits are maximized across society but biased in favour of the poorest and most food-insecure.

Given that many of the world's estimated 800 million food-insecure people are also subsistence farmers, one enduring concern about new technology is that it may affect small landholders, and indigenous farmers' ability to sustain their livelihood. This concern is usually debated in the context of traditional knowledge, farmers' privileges to save and reuse seed and the various national and international laws and treaties that assign and mediate property rights related to genetic materials in seeds. Kolady (Chapter 32) reviews the evolution of this topic, examines the international institutional structure of treaties and concludes that while a system of sorts is now in place, it has differential value depending on the farmer and governance capacity domestically and is a challenge to enforce due to the diversity of actors and venues.

The action arenas considered in this part of the *Handbook* are in many cases driven by and are often linked together by two recent innovative processes. In the past generation the rise of the media, especially electronic sources and the Internet, and the emergence of planned and purposeful efforts by governments to formally engage and to proactively facilitate exchanges with citizens and NGOs have ensured sustained and expansive dialogues about the appropriate choices for agricultural biotechnology. Medlock and Einsiedel (Chapter 33) assert that agricultural biotechnology became an iconic policy issue worldwide in the 1990s, crystallizing growing public concerns about the overall governance of science and technology developments. Concerns included impacts of the commercialization of science, including issues of ownership and control, the adequacy of risk assessment and regulatory processes, the role of technology in advancing globalization, social justice and the voice of citizens in shaping future trajectories of new technologies. In response, governments worldwide embarked on a wave of experimentation with new methods of public engagement, many based on new models of dialogue and deliberation, as a way to rebuild public trust and manage controversy. Medlock and Einsiedel examine the theoretical underpinnings of democratic engagement, review the diversity of methods, focusing on the wide range of citizens' consensus conferences held on the matter of biotechnology, and offer a review of the frameworks for evaluating public participation. They conclude that these processes, while converging on a set of common practices, are not perfect. They often generate significant friction between participants and sponsors, they tend to deliver precautionary, conditional advice and it is unclear what influence, if any, they have on policy outcomes. As a means of examining the application of democratic engagement, Zilberman, Kaplan, Kim and Waterfield (Chapter 34) provide an examination of both sides of the debate in California's recent Proposition 37 on the labelling of GM food products – which was narrowly defeated in the 2012 vote.

The media has become a battleground for ideas and influence. While traditional print and broadcast media remain influential, the emergence of the Internet and all of its attendant activities has fundamentally changed debate and discourse. The 24/7, global system of communications has empowered new actors and enabled new strategies for getting messages and ideas disseminated. Ryan (Chapter 35) addresses these phenomena through the lens of marketing, examining the rise of new actors and the sharpening of messages (what she calls mythmaking) and discussing the response from industry and government. Along the way, all participants – industry, government, NGOs, activists and

scientists – have been challenged to adapt. In many ways, it is probably too early to fully comprehend the impact of these changes on our ability to structure action arenas and make evidence-informed decisions.

4.3 Part III: Outcomes

Technology changes our production and consumption possibilities, but only if it is used. The chapters in part III explore the impacts and outcomes of the application of biotechnology in a number of different ways. An array of chapters use comparative statics to assess the actual or potential impact of GM traits on a number of crops, including those which have achieved large areas of cultivation, those that are planned but not yet in the market and those which failed. A second group of chapters looks at the meta-effects of biotechnology in agriculture and development, using comparative statics and partial equilibrium analyses to assess the absolute and relative impacts of the cumulative adoption of an array of first generation traits.

The analyses of the impact of GM technologies on the farm economy vary significantly by crop and region; a wide range of approaches are used, including farm-level surveys, producer and consumer surveys and comparative static econometric models. All of the studies converge on a set of common findings: developers have some market power and when able to get a product to the market, generally make a decent return; farmers who adopt gain a mix of pecuniary (higher yield, lower cost or risk management) or non-pecuniary (convenience) benefits; non-adopting farmers almost always lose, as yield gains by adopters drive down market prices; farmer gains tend to be somewhat transitory, as one-time yield gains are eroded by lower long-term prices; consumers in aggregate unambiguously gain due to lower prices; consumers who have strong preferences for goods differentiated by production methods may gain or lose; and new technologies tend to be pro-trade, as adoption and production of GM crops is concentrated in exporting countries.

Nevertheless, there are some notable features in each crop. Fernandez-Cornejo and Wechsler (Chapter 36) examine soybeans, arguably the most important and most global crop, with more than half of its production in developing countries. A key differentiating feature here is that most of the gains come in the form of non-pecuniary benefits. Alston, Kalaitzandonakes and Kruse (Chapter 45) extend the analysis and use a multi-sectoral, partial equilibrium model to assess the impact of this critical technology both on adopters and others. Their analysis offers compelling evidence of the importance of considering the spillovers between areas adopting technologies and both non-adopters and competitive sectors.

Carpenter, Gouse and Yorobe assess the impact of maize/corn (Chapter 37). *Bacillus thuringiensis* (Bt) corn performs more as an insurance product, so that gains in years of high pest pressures often offset the premiums paid in low pressure years. Stacked corn varieties are on the upswing, heralding a new business model. Vitale, Vognan and Ouattarra (Chapter 38) note that Bt cotton is now a critical crop crossing between the developed and developing world and is a core part of the bioscience strategy in China, India and parts of Africa. Gains to producers come either from lower costs (if farmers were previously intensively managing pests using chemicals) or higher yields (if farmers were not managing pests), but seldom both. Brewin and Malla (Chapter 39) note that

canola is somewhat different, in that unlike the other three large-area crops, it was neither developed in, nor is its core market in, the US. This mostly Canadian innovation has a higher degree of competition (in that three MNEs hotly contest for market share for HR varieties), developers have both successfully developed and commercialized second and third generation GM traits and there is a long and successful experience in managing industrial and food varieties in the same landscape. Gonsalves and Gonsalves (Chapter 40) tell the fascinating story of the development and promotion of a technology, virus resistance in papaya, that for many farmers is the difference between operating or not. They discuss the long and difficult route to commercialization, with optimal global uptake and use still stalled by slow or incomplete regulatory assessments in key producing areas. Dillen and Demont (Chapter 41) note that while sugar beets present a good vector for GM traits because of the low risk of gene flow and the potential to generate significant commercial returns, adoption remains limited due to an inability to get approved in the EU. In this sense, their study shows the opportunity cost of ineffective regulatory structures. Demont, Chen, Ye and Stein (Chapter 42) similarly examine rice, which has been promoted for decades as an important crop that could be enhanced through genetic modification but that has only just reached the market in recent years. This is particularly important as GM rice is projected to have significant potential to address poverty reduction and health in food-insecure regions of the world.

A number of authors were invited to undertake more comprehensive studies of the impact of new technologies on the broader economy. The difference between comparative static and meta effects is significant and important for understanding the role of biotechnology in agriculture and development. Frisvold and Reeves (Chapter 43) undertook an analysis of the comparative statics studies in each of the product areas to assess the aggregate effects on adopters, non-adopters, investors and consumers. Their conclusions support the emerging consensus from the product-specific chapters. While critics of agricultural biotechnology have expressed serious concerns that all of the benefits, especially in developing countries, accrue to technology development firms, this clearly is not, and never has been, the case. In some instances, the adoption benefits in developing countries actually lie more heavily with producers than any other stakeholder, but this is frequently due to the lack of rigorous IPRs or inability to enforce IPRs in that specific country. Even when enforceable and reliable IPRs exist in a developing country, the majority of the benefits from adopting GM crops lie with producers. Raney, Adenle and Matuschke (Chapter 44) go on to discuss the policy implications flowing from these findings. Finally, Alston, Kalaitzandonakes and Kruse (Chapter 45) report the results of their effort to develop a partial equilibrium model to estimate the gross and net effects of the introduction of GM traits, both on adopters and targeted crops and on non-adopters and consumers. The conclusion is that the gains from GM crops to date exceed US\$40 billion per year, but that number varies depending on the overall market context. Tight markets drive out gains while loose markets amplify gains. Moreover, consumers ultimately gain virtually all of the net benefits, farmers who are early adopters gain, but those gains diminish over time, and crop sectors (for example wheat) and individual farmers that do not use the technology unambiguously are worse off than if the technology had not been used. In short, this technology in some ways has amplified the longstanding technology treadmill that farmers are tied to.

A second category of studies in Part III looks at the ‘wannabes’ and failures. Wilson

(Chapter 46) discusses wheat, which, as one of the most important food grains, was an early target for genetic modification. When a candidate GM event, Monsanto's Roundup Ready herbicide tolerance, was presented for assessment in Canada and the US, it was roundly criticized by all involved and the technology was suspended. While this was viewed as a victory for anti-GM activists and farm populism over the giant Monsanto, in the longer term it has simply perpetuated the decline in wheat's relative competitiveness with crops that are adapting and adopting GM technologies. Recently this has led to a renewal of interest in investigating how GM technologies in wheat might reverse this trend. Rizvi and Scoles (Chapter 47) tell a somewhat similar story for barley, oats and rye, three other small grains popular in crop rotations around the world. Partly in response to the pushback on GM wheat, and partly due to the smaller scale of these crops, efforts to date on these crops have focused on using biotechnology tools (for example genomics, molecular marker assisted selection) rather than transgenics. Breeders generally prefer mutagenic techniques, which in most markets are not regulated to the same extent as GM technologies. There have been efforts to transform each of these crops using transgene technologies, but none of the results have been presented for regulatory review or commercial evaluation. Kikulwe, Falck-Zepeda and Wessler (Chapter 48) look at the prospects for bananas in Africa, reporting on significant potential that they expect will be realized shortly. Williams and Kerr (Chapter 49) look at one of the highly touted industrial applications, GM feedstock for biofuels, concluding that in spite of the best of intentions and an array of proscriptive regulations and programming, the promise is unlikely to be realized in quite the way proponents and developers expect. Finally, Khachatourians (Chapter 50) looks forward to the long-touted future of a bio-industrial future, where plants will be used for a range of non-industrial purposes, including: producing industrial proteins, fibres and molecules; phytoremediating contaminated soils and water; and producing critical pharmaceutical proteins and enzymes in plant hosts at a lower cost, greater scale and higher purity than conventional methods. While each opportunity sounds exciting, a subtle subtext to Khachatourians' chapter is that we need to hope for the best but plan for the most likely – benefits from this type of venture are some ways off yet.

Meanwhile there are a few cases of products that were developed, approved by regulators and commercialized, but then withdrawn. Studying failure can sometimes tell us more than studying success. Ryan and McHughen (Chapter 51) examine three headline-making failures: tomatoes, the first large-scale commercial GM crop; potatoes; and flax. Their message is that despite numerous tests for safety of products passing through the rigorous regulatory approval processes, good science is no guarantee for commercial success of GM food or crop technologies. The introduction of innovative technologies for tomato, potato and flax precipitated well-timed anti-technology programmes that essentially rendered these good products and technologies null and void. While it is difficult to calculate the cost of value lost and costs of withdrawal of these products from the market, it is evident that these costs are significant.

5 CONCLUSIONS

Handbooks are not usually intended to lead to grand conclusions and insights because they are not driven by a single thesis in support of which evidence and argument are

amassed. Rather, Handbooks consolidate themes and topics to aid further investigation of a larger problem. In this sense, the three interrelated, three-pronged approaches described above create an organizational and interpretive framework for the chapters in this *Handbook*. Reflecting back on the elements of that framework – the epistemic criteria, the IAD framework and the models, methods and metrics – one can say, with some certainty, that biotechnology has engaged an array of purposeful actors, stimulated an array of institutional innovation, precipitated and focused dialogue and research on a number of concerns that, while centred on agriculture, are relevant to a significant number of other areas, and ultimately is generating value. Along the way it creates both winners and losers, which generates policy pressure.

Nevertheless, the impressive contributions in this *Handbook* raise a number of conceptual and methodological issues. In the first instance, while the standard performance indicators and conventional models and methods used to assess agbiotech can deliver useful information about how effectively closed-system technical problems have been solved, they often offer limited insight into how science and technology performs in a broader social context. New methods to provide this composite appraisal are needed to tackle challenging questions about the opportunities, constraints and governance of agricultural biotechnology. A number of emerging methods – such as complexity theory and purposeful foresighting – offer interesting prospects for assisting in understanding the dynamics of change in the field.

There is no certainty regarding which models of coordination and governance are most effective in advancing agricultural biotechnology innovation. Several approaches that assess and encourage social acceptance and use can be found; similarly, a range of public, private and collective models of innovation governance exist. Mostly, these differ along disciplinary lines, according to different interpretations of the actors, their motivations, relationships and normal practices. Various models used in other research contexts have been adapted, tested and incorporated into new models related to the social acceptance, adoption, uptake and governance of agricultural biotechnology. Examples can be found in mathematical models that measure evasiveness or the threats of weediness, simulation models on pest resistance or governance models on risk.

The current narrow set of metrics for the assessment of innovation and the resulting social and economic benefits from agricultural biotechnology research is incomplete and often misleading. These measures simply define the tip of the innovation iceberg; most of the critical processes, outcomes and impacts remain uncharacterized or ignored. The methods and models that have been developed and tested must ultimately be grounded in measures that better capture social causes and effects of innovation. The advent of boundary-crossing science and technology that destabilizes the regulatory environment, together with awareness of the far-reaching social and environmental effects of innovation, increases the demand for meaningful measures of innovation (Phillips et al., 2012).

NOTE

1. This section draws on the work of Munim (2011); this is a partial précis of his analysis of the IAD applied to biotechnology.

REFERENCES

- Economist, The* (2013), 'The world's fastest-growing continent: aspiring Africa', available at: <http://www.economist.com/news/leaders/21572773-pride-africas-achievements-should-be-coupled-determination-make-even-faster>, accessed 17 April 2013.
- James, C. (2013), 'Global status of commercialized biotech/GM crops: 2012', *International Service for the Acquisition of Agri-Biotech Applications (ISAAA) Brief*, 44–2012, ISAAA, Ithaca, NY: Cornell, available at <http://www.isaaa.org/resources/publications/briefs/44/executivesummary/default.asp>, accessed 8 April 2013.
- Kuhn, T. (1970), *The Structure of Scientific Revolutions*, 2nd edn, Chicago, III: University of Chicago Press.
- Leamer, E. (1983), 'Let's take the con out of econometrics', *American Economic Review*, **73**(1), 31–43.
- Leydesdorff, L. and H. Etzkowitz (1998), 'The Triple Helix as a model for innovation studies', *Science and Public Policy*, **25**(3), 195–203.
- Lundvall, B.-Å. (ed.) (1992), *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*, London: Pinter.
- McCluskey, D. (1983), 'The rhetoric of economics', *Journal of Economic Literature*, **31**(2), 482–504.
- McGinnis, M.D. (2011), 'An introduction to IAD and the language of the Ostrom workshop: a simple guide to a complex framework', *Policy Studies Journal*, **39**(1), 169–83.
- Munim, A-U. (2011), 'An exploration of an institutional and behavioural analytic framework for technology transfer and commercialization partnerships', unpublished MPP thesis, University of Saskatchewan, available at: <http://ecommons.usask.ca/handle/10388/ETD-2011-08-64>, accessed 17 April 2013.
- Nelson, R. (1993), *National Innovation Systems: A Comparative Analysis*, Oxford: Oxford University Press.
- Ostrom, E. (2005), *Understanding Institutional Diversity*, Princeton, NJ: Princeton University Press.
- Phillips, P. (2007), *Governing Transformative Technological Innovation: Who's in Charge?*, Cheltenham, UK and Northampton, MA, USA: Edward Elgar Publishing.
- Phillips, P., G. Webb, J. Karwandy and C. Ryan (2012), *Innovation in Agri-food Research Systems: Theory and Case Studies*, Wallingford: CABI.
- Porter, M. (1990), *The Competitive Advantage of Nations*, New York: Free Press.
- Simon, H.A. (1955), 'A behavioural model of rational choice', *The Quarterly Journal of Economics*, **69**(1), 99–118.
- Stone, D. (1989), 'Causal stories and the formation of policy agendas', *Political Science Quarterly*, **104**(2), 281–300.