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The Political Economy of Bundling Socio-Technical Innovations to Transform Agri-Food Systems

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9.1 The Imperative and Challenge of Agri-Food Systems Transformation

The world has enjoyed remarkable agronomic, economic, environmental, and nutritional advances thanks to institutional and technological innovations in agri-food systems (AFS) over the past century. A chorus of prominent recent papers and reports nonetheless emphasizes the need to broaden AFS objectives beyond a longstanding, near-singular focus on agricultural productivity growth, the central target of agricultural research and development (R&D) efforts in the high-income world and under the umbrella of the Green Revolution over the past century (IPBES 2019; IPCC 2019; Messerli et al. 2019, Willett et al. 2019, GloPan 2020; Herrero et al. 2020; HLPE 2020; Barrett 2021; von Braun et al 2021; Barrett et al. 2022). The undeniable climate, environmental, health and social justice consequences of consistently prioritizing higher staple crop yields increasingly now compel embrace of multiple AFS objectives, reflecting AFS' central role in driving health and nutrition outcomes, supporting livelihoods, and influencing—and being affected by—natural phenomena. While the exact language varies among documents, the calls are reasonably uniform for accelerating transformation toward what Barrett et al. (2022) term healthy, equitable, resilient, and sustainable (HERS) AFSs. Productivity growth remains imperative, but AFS transformation increasingly must attend to multiple HERS objectives, above all in the low-and-middle-income countries (LMICs) where virtually all food demand growth will occur this century.

AFS transformation is clearly feasible. A vast array of new science-and-engineering-based discoveries exist at various stages of technological readiness, each capable of helping significantly advance one or more of the HERS goals. The promise of these discoveries is manifest in accelerating private investment, with a record US$52 billion of new funding flowing into agrifood tech startups in 2021, an

Christopher B. Barrett, *The Political Economy of Bundling Socio-Technical Innovations to Transform Agri-Food Systems*. In: *The Political Economy of Food System Transformation*. Edited by: Danielle Resnick and Johan Swinnen, Oxford University Press. © Christopher B. Barrett (2023). DOI: 10.1093/oso/9780198882121.003.0009

85 percent increase over 2020 and a roughly six-fold increase on the $9 billion flow just five years earlier (AgFunder 2022). Furthermore, a rapidly rising share of those investments occur in LMICs in Asia, Africa, and Latin America. Policy reforms similarly exhibit tremendous capacity to unlock AFS potential, as perhaps manifest most clearly in the dramatic advances China and Vietnam made following significant policy changes from the late 1970s through the late 1990s (Christiaensen 2013; Liu et al. 2020). The opportunities afforded by scientific breakthroughs and institutional and policy reforms create a wealth of exciting options to advance AFS transformation, toward any or several of the HERS objectives.

Interest in and opinions on the desired direction, pace, and mode(s) of AFS transformation differ dramatically, however, as do associated policy prescriptions. These differences of self-interest and opinion pose the thorniest challenge to accelerating AFS transformation. The scientific challenges, though formidable, rarely pose the main obstacles to progress. Rather, the most imposing challenges involve the human relations surrounding the political process of determining whose interests and opinions prevail in the contest to shape AFS transformation.

This is challenging because the embrace of multiple AFS objectives necessarily introduces tradeoffs among competing goals. Not only do different people and organizations stand to benefit or lose differentially from any given policy or technology as regards any one goal, but their preferences also vary among goals. Moreover, an assessment of the impact pathways of a wide range of emerging AFS innovations finds that each one is expected to have adverse impacts on at least one of the sustainable development goals (SDGs), usually through indirect, general equilibrium and/or ecological effects (Herrero et al. 2021). Those who care intensively about an outcome that may be adversely affected by an innovation may mobilize to obstruct its emergence and scaling, even if it yields enormous gains in other dimensions.

Furthermore, new technologies, policies, and institutions do not emerge and scale in a vacuum. They are shaped by prevailing power dynamics within the body politic and the economy. Long-run visions of economic, environmental, or other gains rarely carry the day. Short-run political expediency and profitability dominate the political calculus of most powerful decision-makers in government, business, and even the not-for-profit sector. Thus, the challenge of AFS transformation surrounds not the feasibility of marshaling any of hundreds of scientific or institutional innovations now emerging or on the horizon but rather stems from the complexity of assembling coalitions of parties with sufficient influence to enable the emergence and scaling of contextually appropriate socio-technical innovation bundles (Barrett et al. 2022).

Scientists seeking to help accelerate AFS transformation need to take these inconvenient realities seriously. We must take time to think through the competing interests of different groups and the sociopolitical mechanisms through which those groups interact to shape the incentives and constraints that drive most

AFS transformation. Study of these inherently political phenomena can help us anticipate obstacles to diffusing and scaling innovations that appeal in principle.

The central claim of this chapter is that attention paid to the political economy of innovations can inform strategies to integrate one's favored interventions with other, complementary ones, to build socio-technical innovation bundles (Barrett et al. 2022): the contextually fit-for-purpose combinations of "soft" and "hard" innovations designed keeping firmly in mind with both tradeoffs among objectives and feedback within and among adaptive processes. The (typically large) set of innovations and technologies that satisfy the Kaldor-Hicks compensation criterion offers a menu of options, some combinations of which can motivate concerted support from a coalition of interests sufficient to accelerate AFS transformation. Conversely, AFS transformation is impeded by failure to build such coalitions, sometimes impeded by excessive concentration of power such that some parties do not see a need to compromise or by misinformation that undermines latent coalitions.

9.2 Why Socio-Technical Bundles?

The central message of Barrett et al. (2022) is that bundled innovations are a necessary condition for AFS transformation; magic bullet solutions simply do not exist. Three core reasons drive the need to bundle "socio" and "technical" innovations. First, policies, institutions and culture—the "socio" part—can either enable or impede the diffusion and adaptation of science-and-engineering-based innovations. This naturally turns cultural (e.g., cuisine), institutional (e.g., organizational and contracting forms), and policy innovations into complements to biochemical, digital, ecological, genetic, mechanical, and other technical advances.

Some observers refer to these "softer" cultural, institutional and policy complements as an "enabling environment" for technological change. That framing, however, makes culture, institutions and policies seem exogenous, even immutable, ignoring that they evolve alongside technical innovations through a range of feedback mechanisms. Consider one very current example. As new plant-based and cellular alternative protein products emerge from academic, government and industrial labs and enter grocery stores, institutional cafeterias, and restaurants, incumbent producers of animal-source foods push for restrictions against labeling these new products "meat" and demand that regulators develop new criteria for assuring the safety of novel products, often insinuating the novel products are somehow less healthy or safe than established ones. Meanwhile, alternative protein advocates launch new angel and venture investment vehicles to support startups in this space, generate public service programming around the health, climate, and animal welfare benefits of the new products, and organize cooking shows and widely disseminate recipes to help stimulate grassroots uptake.

The "socio" innovations begotten by scientific innovations are themselves impressive, aimed at either actively reinforcing or obstructing the emergence of a novel biotechnological product.

As elaborated a bit further below, a central lesson of the tremendous success in Green Revolution-era genetic advances in rice concerns the centrality of complementary, bundled rural infrastructure, services, and policies with scientific advances. That reality comes into especially clear focus when one juxtaposes the tremendous successes of the Green Revolution era modern rice varieties with the as-yet-unrealized promise of "golden rice." Although golden rice represents a remarkable scientific advance—the world's first transgenic, biofortified staple cereal—it lacked similar supporting constituencies necessary to bundle enabling institutions and policies to turn exciting science into impactful AFS transformation—and to overcome predictable political opposition from activists protesting the use of transgenic methods.

The second reason bundling is necessary is that rarely does any singular innovation fully solve a problem. Different combinations of institutional, policy and technological innovations will be appropriate among and within distinct contexts. That is true not just at macro scale, e.g., in the rather obvious differences in innovations needed in smallholder dairying systems of the east African highlands, versus northwestern Europe's modest-sized, multifunctional dairy farms, as compared to massive industrial scale dairy farms in the western United States. This structural heterogeneity exists equally within countries. A different form of complementarity arises in this case, wherein distinct subpopulations need different innovations, therefore addressing a macro-scale challenge requires heterogeneous, bundled interventions at more disaggregated, micro- and meso-levels.

A canonical example concerns addressing the micronutrient deficiencies that are the most prevalent diet-based cause of ill health worldwide, affecting more people than hunger (i.e., caloric undernourishment) or obesity and overweight. For example, the best entry point for reducing iron-deficiency anemia (IDA) depends on a target subpopulation's income, dietary and nutritional awareness, age, and gender, whether they farm or not, and conditional on them farming, whether they sell little, most, or all of their harvested output. For some adult subpopulations, income transfers, perhaps coupled with quasi-price incentives, and nutrition education may induce changes in food purchasing and dietary behaviors that remedy IDA.[1] For children, school feeding programs may offer a more direct path to dietary change that boosts iron intake (van Stuijvenberg 2005). But inducing dietary change is hard, so in many contexts industrial fortification of processed

[1] A nice example from the United States is the Double Up Food Bucks program, which doubles that portion of government-provided cash-based food assistance (from the Supplemental Nutrition Assistance Program, SNAP) that a beneficiary spends on fresh fruits and vegetables. Currently, only about half of the states employ Double Up Food Bucks. See Wielenga et al. (2020) for evidence on the program's food procurement impacts.

foods appears more impactful at scale (Huma et al. 2007). Other strategies may be needed for more remote, semi-subsistence populations, however, because their dietary intake comes overwhelmingly from home production and consumption. For some, the most cost-effective approach might be to induce acquisition and maintenance of livestock to boost intake of iron-rich animal-sourced foods (Rawlins et al. 2014) or the introduction of biofortified crop varieties that increase iron concentrations in the grains or legumes individuals consume (Finkelstein et al. 2017). Unfortunately, little research has yet explored how best to bundle these various interventions to combat the IDA challenge specifically nor micronutrient deficiencies more generally (Barrett and Bevis 2015).

The third reason to bundle, and the focus of the remainder of this chapter, is political economy. The tradeoffs inherent to every innovation inevitably generate (at least latent) opposition. Conservatism—i.e., resistance to change—is a natural human impulse, a risk averse response to the prospect that change might leave one worse off.[2] Moreover, every innovation in isolation causes some adverse effect somewhere in general equilibrium; that's the macroeconomic lesson of Dutch disease[3] and has been shown in the case of AFS innovations (Herrero et al. 2021). So even those people who enthusiastically favor change will have counterparts who clearly do not favor that same change. This innate conservative tendency is reinforced by humans' greater sensitivity to forces working against them—headwinds—than to those that discreetly favor them—tailwinds (Davidai and Gilovich 2016). If people are more cognizant of potentially bad impacts than they are to potentially supportive processes, then they will resist changes more often than serves their own self-interests.[4] Conservatism therefore works against necessary AFS transformations based on bundling socio-technical innovations.

Hence the need to bundle innovations to form a coalition of parties, each of whom embrace at least one of the bundled innovations and can tolerate the other innovation(s) conditional on getting their preferred innovation included. Bundling innovations can enable the formation of coalitions of a critical mass of

[2] Slightly more formally, if there exists some nonzero probability that change will render one worse off as compared to no change, then a rational agent would only favor change over no change under very strong assumptions about the nature of their preferences. The distribution of outcomes under "change" can never stochastically dominate that under "no change." One needs a special case of a particular class of utility function to generate a welfare ordering that favors change for anyone who perceives a chance of an adverse outcome.

[3] "Dutch disease" refers to the economic damage wrought from windfall gains. Its origin comes from the decline of the Netherlands' manufacturing sector following the discovery of massive natural gas reserves that yielded a huge inflow of foreign exchange from the sale of natural gas, which caused the currency to appreciate, making tradable Dutch manufactured (and agricultural) goods less internationally competitive. The concept has been applied to foreign aid and other sources of windfall revenue as well. The point is that what appears an unambiguous gain turns into a mixed bag due to feedback effects through the broader bioeconomy.

[4] This is also a key reason why some policies based on "carrots" commonly succeed politically where analytically superior designs based on "sticks" fail. Consider, for example, the success of subsidy-based policies to reduce greenhouse gas emissions and the failure of analytically superior, tax-based approaches to achieve the same goals.

interested parties, thereby overcoming the tradeoffs inherent to all innovations in a multi-objective, pluralistic body politic, as well as the natural human tendency toward conservativism.

Socio-technical bundling may be essential for the first two reasons, i.e., there exists some sort of complementarity among distinct innovations that makes them more attractive and impactful when implemented together than in isolation, especially within a heterogeneous population. But "identifying and bundling the right innovations is an intrinsically social process, one that demands cooperation that is in shorter supply than are brilliant scientific insights" (Barrett et al. 2022).

9.3 Building Coalitions for Bundling: Insights from the Kaldor-Hicks Compensation Principle

A brief digression into welfare economics can help clarify concepts before I proceed. The original utilitarian philosophers of the 18th, 19th, and early 20th centuries imagined cardinal, interpersonally comparable measures of individual welfare such that one could aggregate individuals' welfare gains or losses from any innovation and thereby identify "socially optimal" (in the utilitarian sense) policies for any given society. In an era in which autocracy was the dominant mode of governance, one could plausibly (if naively optimistic) imagine a technocratic model guiding decisions made by a benevolent dictator. But the combination of the rise of democratic governance—in part because few autocrats proved benevolent!—and advances in economic theory—which evolved to understand that individual welfare is ordinal and not interpersonally comparable—together undermined the old-fashioned, utilitarian approach to political economy. One could no longer assume that the gains of some more than offset the losses of others. Moreover, even were it true that an innovation would yield net societal gains, one could not impose such a result with sufficiently widespread consent among the governed. Arrow's (1950) famous impossibility theorem drove home the central implications that follow from democratic choice and utility theory: all social choice is necessarily a bargain among a range of parties and few policies reach the idealistic welfare standard of Pareto efficiency.

But welfare economics can still offer useful guidance on political economy. In particular, Kaldor (1939) and Hicks (1939) independently developed compensation criteria to address this challenge. The Kaldor-Hicks criterion holds that an innovation is desirable if and only if those who gain can, in theory, at least fully compensate those who would be harmed and remain better off after such compensatory transfers. For this reason, innovations satisfying the Kaldor-Hicks criterion are sometimes labeled "potential Pareto improvements." Kaldor-Hicks still relies on utilitarian reasoning but jettisons the aggregation across individuals and interpersonal comparisons. The weaknesses of the Kaldor-Hicks compensation principle are that (i) no prospective losers will be satisfied by the mere theoretical prospect of being left whole through compensation, and (ii) compensation can be difficult to implement and sequence in a manner that is renegotiation-proof and neither excessively distortionary nor wasteful.

The analytical apparatus of Kaldor-Hicks is nonetheless useful to analyzing the political economy of AFS transformation because it underscores a key benefit of bundling. By bundling multiple innovations, each of which advances the goals of distinct constituencies and thereby de facto compensates for any losses created by another innovation, one can build a sufficiently influential coalition to effect change. Indeed, compensatory transfers to turn the potential Pareto improvements identified by the Kaldor-Hicks criterion into actual Pareto improvements is a special case of bundling, of the innovation and a transfer.[5]

The Kaldor-Hicks compensation criterion thereby provides a means of identifying candidate innovations to bundle. Any AFS innovation that satisfies the Kaldor-Hicks criterion generates sufficient gains for some constituency that some portion of those benefits could be used to compensate other constituencies who would lose from that innovation. But one does not need to design compensation mechanisms—although transfer payments could be one of the innovations in a bundle—if there exist combinations of innovations that accomplish the same goal. Indeed, if one bundles multiple potential Pareto improvements, the net gains are necessarily larger than one realizes under any one of the potential Pareto improvements, made politically feasible with a transfer payment, since transfer payments are intrinsically zero-sum.[6] Hence the political economy appeal of bundling multiple socio and technical innovations. Bundling can enhance gains while overcoming the obstacles to widespread acceptance of any single cultural, institutional, policy, or technical innovation.

Bundling is perhaps especially attractive and feasible among those who share a desire to encourage AFS transformation but who prioritize different outcomes, say better animal welfare and cleaner water and reduced micronutrient deficiencies. Few, if any, single innovations can deliver on all such aspirations, and certainly not in equal measure (Herrero et al. 2021). But a form of compensation can be support for an innovation to which one might object in isolation. Bundle together the right combination of multiple such innovations and one winds up with a critical mass of constituencies that support the bundle of innovations. One can thereby generate Pareto improvement, in which no one is worse off and at least some are

[5] A good deal of contemporary agricultural policy in Europe and North America relies heavily on such compensating instruments. See chapter 13 of Swinnen (2018) for a nice exposition and more detailed references.

[6] If transfer payments are distortionary—as is true, for example, of most payments tied to producer behaviors—then transfers could be worse than zero-sum, reducing the scope for potential Pareto improvements and beneficial bundling of transfer payments with other innovations to generate actual Pareto improving policy bundles.

better off (Barrett et al. 2011). The Kaldor-Hicks criterion defines a set of innovations that create a space for political coalition formation to overcome the natural obstructionism of humans' conservative nature.

9.4 The Roles of Institutions, Power, Information, and Trust

The Kaldor-Hicks criterion provides a useful tool for identifying candidate innovations to bundle. But it offers no roadmap for how to craft a bundle that can create a coalition necessary to advance. One must think in terms of how to build political coalitions because human agency is both the main engine of and the primary obstacle to AFS transformation. All humans have both objectives and blind spots. Furthermore, rarely do individuals' varied objectives and blind spots coincide perfectly. Resolving individuals' and organizations' differing interests and blind spots is the task of coalition formation.

Coalition formation necessarily turns on societal institutions, what Douglass North (1991) famously defined as "the humanly devised constraints that structure political, economic and social interaction." We must look to the rules that regulate the sociopolitical processes through which innovation and transformation are negotiated and co-created. Innovation is a strategic game in which differing parties undertake actions aware of, influenced by, and trying to shape prospective responses by others. As with all strategic games, parties' interactions and equilibrium outcomes and disequilibrium dynamics all follow from the incentives and constraints agents face, the information they possess and create, the degree of trust among them—which drives the salience and importance of formal rules—and their power to bring about their preferred outcomes. Thus, institutions (the rules that guide interactions), information, trust, and power ultimately jointly shape the political economy of innovation bundling.

Bundling socioeconomic and technical innovations to transform agri-food systems requires the coordinated exercise of human agency through sociopolitical processes in which diverse AFS actors both empower each other and hold all parties accountable. Arguably the greatest challenge to coalition formation is the excessive concentration of (economic and/or political) power. When power gets too concentrated, the powerful have little incentive to compromise and can too frequently dodge accountability to others for any harms that arise from imposing their will. The powerful may be inclined to impose innovations that suit their interests but harm others because their power obviates the need to build coalitions to bundle innovations that yield Pareto improvements. Or the powerful may obstruct innovations that might threaten their position. The relationship between power and innovation is quite ambiguous. But power commonly obstructs coalition formation of the sort needed to advance bundling that can achieve (or at least approach) Pareto improvements across multiple HERS objectives.

Clear rules to constrain the injurious exercise of power may be less necessary in small communities if community members know and trust their leaders. Strong communities can foster trust, generating mechanisms that endogenously induce good behavior and enforce compliance with the community's unwritten rules (Barrett 1997; Platteau 2000; Fafchamps 2003), although one must be careful not to over-romanticize communities, many of which are disturbingly dysfunctional (Barrett et al. 2001). The gains from trade and associated externalities (e.g., climate change) that span vast distances, however, typically exceed the scope for trust-based interactions at community scale and compel complementing trust with formal rules, as well as accountability and enforcement mechanisms (Platteau 2000). One must trust but verify and enforce.

Hence the foundational importance of the "rule of law" as a check on excessively concentrated power. Of course, the setting and enforcement of rules is itself a political task (Gibson et al. 2005). And rules and the rules-making fora must match the scope of the actors involved, ideally be situated at the minimum scale necessary to internalize the various externalities, following the principle of subsidiarity. Thus, for transnational matters, for example, one necessarily needs multinational fora, such as the Codex Alimentarius or the World Trade Organization. But for subnational watershed scale phenomena, a far more limited scope of participants is optimal.

Myopia is as intrinsic to the human condition as conservativism. The powerful too often underestimate the likelihood that they will eventually fall from power and become passively subject to others imposing their will. It's easy to imagine that behind a Rawlsian veil of ignorance—i.e., in an initial state before one learns one's station in society (Rawls 1971)—all persons would agree to clear, firm limits on the unilateral exercise of power. But once one holds sufficient power that it seems feasible to impose one's preferences, like a utilitarian dictator, then the temptation grows to dismantle or ignore rules. It just takes one deviant dictator who unusually heavily discounts the future in favor of immediate gains to unravel the rules—and who gets away with flouting rules—to degrade the quality of institutions. This is especially true because people naturally follow tit-for-tat strategies in repeated games.[7] Hence the critical importance of holding the relatively powerful accountable for their actions and consequences.

An important, counterintuitive source of power stems from what Olson (1965) labeled "the logic of collective action." The basic idea is that small groups in which each member individually enjoys large prospective gains have stronger incentives to engage in collective action than do the members of far larger groups, who may enjoy massive collective prospective gains but small individual gains. This leads the former, smaller group to organize and achieve collective action that commonly

[7] Animal experiments show that behaviors typically follow most recent interactions and fail to integrate remembered experiences over longer timespans (Schweinfurth and Taborsky 2020).

prevails over the latter, larger group, which fails to organize. Thus, a well-organized minority can emerge to dominate political processes, at net cost to society and most of its members.

The logic of collection applies to many individual innovations, the gains from which typically diffuse broadly through general equilibrium price or wage effects or environmental externalities. But a small group of individuals may be highly motivated, e.g., to protect and profit from their intellectual property (IP) rights or favored status in government contracting, or to advance an ideological agenda. They acquire power not because they have the capacity to impose their will unconditionally, but rather because a potentially dominant opposition fails to mobilize itself.

The logic of collective action can be turned to advantage in building coalitions, however. One needs to identify multiple innovations that each satisfy the Kaldor-Hicks criterion—ideally, the innovations are themselves complements, so that the net gains of joint introduction exceed the sum of their independent use—and each of which enjoys a constituency that stands to benefit sufficiently from a particular innovation that it will actively advocate for it. Bundle those innovations together and one has a larger coalition of supporters for the innovation in question. Indeed, the most powerful coalitions commonly combine the strength of organization of small interest groups with the numbers of large, harder-to-organize ones (Swinnen 2018). One can understand creative new ventures like China's Science and Technology Backyards program or the successful emergence and diffusion of Green Revolution rice varieties—both cases described below—as arising from the bundling of innovations that each enjoyed active support from some minority constituency.

Especially as AFS transformation requires increasing uptake of knowledge-intensive innovations, not just technological advances embedded in chemicals, machinery, or seed, the quality of information flow takes on increased importance for ensuring full realization of the prospective gains—and avoidance of prospective harms—from the innovation. But information matters in another, more political way as well. The production and dissemination of information is a very important, specific form of collective action in which those with a strong interest in advancing or opposing an innovation might invest. Information can influence people's opinions about the prospect gains or losses they—or things they care about—face from an innovation. Information can dampen opposition or mobilize support.

The institutional constraints on information matter because of the incentives to produce and circulate misinformation. Some misinformation emerges maliciously, as when an interest group willfully obfuscates as a tactic to gain advantage. But a significant portion arises when untested hypotheses gain a foothold in people's minds and become entrenched through repetition. Indeed, the strongest opinions are often also the most erroneous and held by the least knowledgeable people. That has been shown, for example, in the case of Americans' and Europeans' beliefs about transgenic foods, where "extreme opponents know the least, but think they know the most" (Fernbach et al. 2019). When people are misled as to what serves or does not serve their interests, they can act against their own material interests. That can readily impede accurate identification of options for shared gains following the Kaldor-Hicks criterion.

This matters especially because scientists rarely directly inform policymakers nor even the constituents and lobbyists who nudge policymakers one direction or another. Rather, popular—and increasingly social—media commonly intermediate between scientific and popular discourses. One needs then to recognize that media organizations and individuals have their own interests that condition the description and transmission of information about innovations. For-profit, private media companies will necessarily take short-term profits into consideration in deciding whether or how to cover a story. They may be subject to effective pressure from investors or clients (e.g., major advertisers). Conversely, state-run media can be subject to political pressure from a governing coalition. A free, independent press that is not entirely beholden to commercial interests seems the best bet for reasonably reliable transmission of information. But traditional forms of media are increasingly dwarfed by effectively uncontrolled, private social media, which may leave information especially subject to manipulation.

One explicitly political use of information, perhaps especially misinformation, is to undermine trust in scientific evidence and the scientists who generate both innovations and evidence. Innovations by definition arrive with scant evidence regarding their impacts. Innovations are thus subject to "Knightian uncertainty," meaning there exist unquantifiable, stochastic outcomes rather than a probabilistically quantifiable distribution of outcomes. We economists term the latter "risk" rather than "uncertainty." Knightian uncertainty is important because of humans' inherent conservativism in the face of exposure to a prospective hazard. The precautionary principle formalizes that conservative impulse, holding that one should resist any innovation whose ultimate outcomes are uncertain, especially if there exists any realistic prospect of serious adverse outcomes.

Opponents of innovations therefore work hard to feed prospective opponents' uncertainty, so as to dampen support or even spark active opposition to the innovation in question. Conversely, advocates of innovations must work to reduce uncertainty, hence strict regulatory protocols around what sort of quantifiable evidence must be generated and by what methods in order to secure formal approval of a new innovation.

This leads to the final ingredient behind coalition formation to bundle innovations: trust. People either trust or distrust information and the sources of information. Similarly, they either trust or distrust the producers of and advocates for innovations. The ability to build a coalition depends considerably on the degree of trust among the parties involved because trust sharply reduces the costs of coordination and exchange (Barrett 1997; Platteau 2000; Fafchamps 2003). Coalitions are inherently dynamic, evolving in response to changing conditions, and bundling often requires sequenced implementation or introduction of different innovations. The degree of trust among them affects the likelihood that a coalition forms and persists.

Trust-building is a major advantage of co-creative processes, like participatory plant breeding (Ceccarelli et al. 2009) or China's Science and Technology Backyards program, discussed below. Co-creation can help make more information available to an innovator's partners, but it also builds trust in the information and its source(s). Trust reduces the need for binding, formal rules, and thus lessens the bureaucratic frictions that slow innovative advances. Relative high degrees of trust within southeast Asian societies and their government agencies were arguably part of the recipe for a successful Green Revolution in rice and wheat production, while absence of trust in external scientists, patent holders, and others may have contributed to the slow progress of golden rice, another case discussed below. Transformation accelerators all revolve around human action that generates and shares information and promotes cooperation and trust (Herrero et al. 2020; Barrett et al. 2022). Those who stand to benefit from an innovation that satisfies the Kaldor-Hicks criterion are more inclined to sacrifice some share of their prospective gains with those they trust than with those they do not.

Co-creation processes naturally foster the bundling of socio-technical innovations because different stakeholders join the process with different favored innovations in mind and because each is willing to engage the process because they see the prospective gains from cooperation and compromise. Impactful innovation and bundling can originate among actors anywhere within AFSs, induced by any of a host of motives. So, too, can obstruction. Harnessing the potential inherent to the amazing range of current AFS innovation requires honest, constructive dialogue to co-design contextually appropriate socio-technical bundles of innovations that can enable navigation away from looming dangers and toward a HERS future. Governments and multilateral agencies can try to choreograph some co-creative activities. But most arise serendipitously from decentralized, coordinated actions by public, private, and civil society actors who recognize that they share some common ambitions and opportunities with others.

Co-creative activities necessarily increase human interaction. And increased interaction helps define rules of engagement that constrain the excessive concentration of power, thereby facilitating the flow of (accurate) information, and building and reinforcing trust. Such coalitions can become probabilistically self-reinforcing in the sense that the likelihood of finding common ground increases over time, by both reducing the costs of overcoming distrust and misinformation and facilitating identification of fruitful new opportunities for bundling. Innovations spread more quickly when the technical and economic gains they generate are shared among groups and those groups interact regularly, ideally cooperatively (Rogers 1962; Barrett 1997; Gawande 2013).

9.5 Some Empirical Illustrations

Any of a range of past and current AFS innovations could illustrate the processes described here. Examples from the United States are numerous. For example, one could explore the rise of multifunctional agricultural landscapes in which solar or wind farms combine with crop, livestock, and biogas production, facilitated not just by public subsidies, but at least as much by changes in zoning laws and the regulation of electricity generation along with the extension of rural road and energy infrastructure (Lauer et al. 2018; Pavlenko and Searle 2018). Or one could explore the symbiotic roles played by agricultural and nutritional sciences researchers, the animal welfare lobby, food manufacturers, school systems, and national food regulators in developing alternative proteins to replace animal-sourced products, from the first-generation textured plant-based protein products of the 1970s–80s through more recent plant-based and cell-cultured products (Broad 2019; Neltner 2021; von Kaufman and Skafida 2023). Or how an "Iron Triangle" coalition of agribusiness and shipping industry interests, working with international development and humanitarian nongovernmental organizations (NGOs), reinforced wasteful and relatively ineffective global food aid policies (Barrett and Maxwell 2005) until new scientific evidence and a few courageous NGO leaders dismantled that coalition, engineering rapid advances in humanitarian food assistance (Barrett et al. 2011; Lentz et al. 2013). The following sections draw on three examples from Asia to illustrate the core ideas behind coalitions to build socio-technical bundles.

9.5.1 Example 1: China's Science and Technology Backyards

China's Science and Technology Backyards (STB) program offers a premier example of coalition formation to bundle socio-technical innovations.[8] Starting in 2009, China Agricultural University (CAU) scientists secured support from the central state and the local government in Quzhou, in Zhejiang Province, to launch a participatory research and extension effort aimed at boosting farmers' identification and uptake of yield-improving, resource-conserving farming methods and inputs. Despite China's amazingly rapid technological change, farmers had often been slow to adopt improved production practices, in particular

[8] This section draws heavily on the description in Barrett et al. (2022) as well as Shen et al. (2013), Jiao et al. (2019, 2020) and on helpful, informal input from Profs. Jianbo Shen and Fusuo Zhang.

those that improved soil and water management, and especially if such production choices were perceived as demanding added labor, given growing rural labor scarcity as hundreds of millions of Chinese migrated from the countryside to urban manufacturing and services jobs (Christiaensen 2013).

Distinct constituencies sought related, but different goals. University-based agricultural researchers wanted to develop and publish new science. Farmers wanted new tools they could use in their specific contexts—which varied dramatically across a country as vast and heterogeneous as China—with minimal risk and added cost. Commercial input suppliers needed new markets of sufficient volume and prospective profitability to justify the sunk costs of establishing a new distribution channel and relationships. Each group had pushed for its interests with government, with limited success. They ultimately recognized that although each group would need to adapt its prior practices a bit, the net gains from closer collaboration, with clear responsibilities for each party, were sufficiently large to draw them into a coalition that pushed for STB with government and won essential initial financial support. Strong central and provincial government support was essential to finance the bundled intervention and to hold the different constituencies together in the early years. This case is a good example where concentrated (government) power can accelerate innovation when the powerful perceive innovation in their interests, which the Chinese government clearly has in the case of boosting agricultural productivity and sustainability.

The STB design originates in the idea of localized co-creation. University scientists relocated their research programs from the experimental station to rural villages, renting a "backyard" in many villages where they and their students lived, worked, and studied, interacting intensively with farmers and providing regular, intensive training sessions. As farmers began to enjoy improvements on their own farms by applying lessons learned in the backyard research farms, interest spread and more farmers were attracted to the backyards, turning them into technology dissemination focal points. Local governments were supportive because the researchers were no longer outsiders and farmers were allying with the scientists with whom they worked increasingly closely. Input suppliers enjoyed a significant boost in demand for seed, fertilizer, livestock vaccines, and other commercial inputs, which encouraged them to make free samples available when the next backyard opened, enabling faster replication and spread of the model within and across provinces. Companies could also contribute their new technologies for experimentation, getting rapid, low-cost field trial data to identify which products they should scale or abandon. STBs thereby became multi-actor platforms in which each party was able to advance its own objectives, often compromising a bit on its myopically self-interested goals in order to help advance the broader agenda from which it clearly benefitted.

The result was impressive by any standard. By 2020, the initial intervention has scaled to 127 STBs operating in 23 difference provinces and engaging 29 different scientific research institutes and more than 100 different agricultural extension stations, reaching tens of millions of farmers nationwide. Researchers got access to copious amounts of near-real-time data from a range of experimental and observational studies and the ability to adapt research designs quickly in a participatory research and extension system. The scale and scope of data enabled researchers to more accurately and quickly identify which practices and inputs worked well for which farmers under which conditions. Not only did this generate significant scientific insights and publications, it also accelerated crop yield growth and on-farm soil and water conservation (Zhang et al. 2016). The contextualized results from co-created research reinforced farmers' and input suppliers' confidence in the scientific evidence and thus their willingness both to experiment with new methods and inputs—e.g., formulated fertilizers, new sowing technologies, improved soil management practices—and to cooperate with researchers, accelerating both development and diffusion of improved practices, with major productivity and resource conservation gains (Shen et al. 2013; Zhang et al. 2016; Jiao et al. 2019).

9.5.2 Example 2: Genetic Improvements in Rice

The development of improved, high-yielding varieties of rice and wheat in the 1950s and 1960s are widely considered the spearhead of the Green Revolution (Pingali 2012). Crop yields multiplied several times as modern varieties diffused rapidly in places like India, Mexico, and Pakistan, inducing the award of the 1970 Nobel Peace Prize to a plant breeder and pathologist, Norman Borlaug, widely dubbed the Father of the Green Revolution. Careful analyses consistently find dramatic gains to the poor and the natural environment from the bundled innovations of that era based on the development and diffusion of improved crop varieties, especially rice (David and Otsuka 1994; Evenson and Gollin 2003; Gollin et al. 2021).

Political opposition to the Green Revolution nonetheless existed from the outset.[9] But that opposition was overcome by building coalitions of interest groups that supported agricultural modernization and intensification and that coordinated with and largely trusted one another—e.g., CGIAR Centers with national agricultural research institutes, government agriculture ministries, local rural governments, etc. The Green Revolution offers a powerful lesson on the importance of building coalitions that each favor distinct innovations—e.g., in crop genetics, fertilizer formulation, irrigation engineering, labor-saving machinery designs suitable for small farms—with supporting institutions and policies that facilitate the

[9] These are my oversimplified summaries of a range of lessons kindly imparted to me over the years by others with far greater in-depth knowledge of the Green Revolution era rice advances than I have, including Randy Barker, Bob Evenson, Yujiro Hayami, Bob Herdt, Kei Otsuka, Prabhu Pingali, Vern Ruttan, Peter Timmer, and Mike Walter.

adaptation of scientific discoveries to specific local AFS contexts and the scaling of impacts.

Many observers at the time openly worried that the introduction of improved Green Revolution crop varieties, irrigation, and agrochemicals would benefit wealthier farmers with more land at the expense of poorer smallholders. Others were concerned that the use of agrochemicals would despoil the natural environment, that higher yielding varieties would lead to monocultures that eliminated agrobiodiversity, or that expanded irrigation would disrupt ecosystems' delicate hydrological cycles. These were certainly not irrational concerns.

The inevitable opposition to IR8, IR36, IR64, and other improved rice varieties was overcome, however, in large measure because those genetic advances were bundled with other agricultural innovations (e.g., irrigation, agrochemicals) in which other commercial or government entities had a strong interest and with complementary institutional (e.g., extension services, marketing boards), infrastructural (e.g., rural roads and electrification), and policy changes (e.g., labor, price, and trade) that independently had support and that helped accelerate diffusion and scale up impact (David and Otsuka 1994). In India, Indonesia, and Pakistan—and a generation later, in China and Vietnam (Pingali and Xuan 1992; Huang and Rozelle 1996; Liu et al. 2020)—a complex web of policies emerged that facilitated the creation and maintenance of political coalitions to support a broad suite of rural development interventions that rapidly transformed those nations' AFSs. The Philippines-based International Rice Research Institute (IRRI) was at the heart of much of this work, with deep, longstanding collaborative relationships with national agricultural research and extension services, national water agencies, local seed companies, and technocratic elites throughout governments in south and southeast Asia. Some of the individual institutional or policy changes (e.g., food price stabilization measures) were themselves contentious and may seem ill-advised when considered in isolation. But such measures often proved politically necessary to build the coalition needed to support more directly impactful interventions, such as in improved irrigation systems to enable more precise water control to realize the full potential of the improved rice varieties and better transport systems to facilitate interregional labor migration and the low-cost evacuation of crop surpluses (David and Otsuka 1994).

Contrast the path and impacts of the early Green Revolution improved rice varieties, such as IR8 and later IR64, with the non-impact of an arguably more momentous scientific advance: transgenic golden rice. In 2000, scientists in Germany and Switzerland published scientific details on a new rice variety that biosynthesizes beta carotene, the precursor to vitamin A, after the introduction of genetic material from a species with which rice cannot naturally cross. Golden rice was, quite unusually for a very technical scientific paper, the cover story for the news magazine *Time* (July 31, 2000), under the title "This Rice Could Save a Million Kids a Year." The fanfare was natural, as golden rice was a far more impressive scientific achievement than the semi-dwarf IR8, IR36, or IR64 varieties of the Green Revolution.

Yet it took more than 20 years after the scientific publication to, in 2021, secure the first regulatory approval in a rice-growing LMIC,[10] the Philippines, to release golden rice for commercial cultivation, processing, and sale. By contrast, within 20 years of its introduction, IR64 became the most diffused cereal seed variety in human history and it and its predecessor lines (especially IR8 and IR36) were widely credited with diffusing so broadly as to rescue south and southeast Asia from the famines the region had episodically experienced from the late 1940s until the early 1970s.

Why such strikingly different outcomes from two episodes of genetic improvements in rice, especially given golden rice's scientific superiority? The difference seems to lie in the political economy of the new varieties' release and attempted diffusion.

Golden rice was popularized as a magic bullet solution but was based on a controversial, transgenic method against which popular distrust was building rapidly in the 1990s and early 2000s.[11] Golden rice was developed by university-based researchers half a world away, without deep, longstanding integration into the economic and political institutions of the region and its AFSs. They were easily (mis)portrayed as outsiders inflicting dangerous science on the poor, a sort of agricultural Dr. Jekyll. Even though much of that (mis)information was produced and propagated by other outsides—e.g., Europe-based environmental NGOs—the lack of trust in or coordination with the external scientists made it relatively easy to sow doubt and uncertainty around this innovation and thereby obstruct its emergence.

Further, the technologies used to create golden rice were subject to a dense thicket of patents that took years to navigate, so golden rice advocates had to divide their time between parrying staunch anti-transgenic opponents, building relationships with local government and business leaders, and navigating a legal quagmire with those disinterested in whether golden rice diffused or not, just with safeguarding their intellectual property rights.

Especially in the 2000s, the technocrats advocating for golden rice failed to build the political coalitions nor to attract the internal, domestic champions to prevail in places like the Philippines, India, and Bangladesh. Notably, over time, as IRRI began to assume greater leadership in the push for golden rice—and as the

[10] Golden rice was previously approved by government regulators as safe in Australia (2017), New Zealand (2017), Canada (2018), and the United States (2018).

[11] See Lynas (2018) for a fascinating account by one of the anti-genetically modified foods movement's original leaders about the role of misinformation and political passions in driving opposition to transgenic seeds. One of Greenpeace's self-described co-founders, Patrick Moore, ultimately left and disavowed the organization, launching a counter-campaign called "Allow Golden Rice Now!" and labeling Greenpeace's ardent opposition to golden rice "a crime against humanity" based on disinformation and scare tactics (http://allowgoldenricenow.org/wordpress/about/).

oppositional tactics of anti-transgenic protest groups turned violent and destructive, turning popular opinion away from them and toward golden rice—progress in IRRI's host nation, the Philippines, accelerated. Ultimately, the Philippines became the nation where golden rice first secured full approvals and commercial release for cultivation, consumption, processing, and trade. Elsewhere in the Global South it has proved slower and more difficult to build coalitions and broker the necessary bundles of supporting policies and institutions. Thus, an incredibly promising technology stays largely on the shelf more than two decades later.

The Green Revolution varieties developed using conventional plant breeding methods succeeded with publicly funded R&D and extension in an environment more trusting of science, and less reliant on private funding and intellectual property protections. The juxtaposition of these advances in rice genetics underscores how innovations that advance one or more productivity, health, environmental, or other objective face predictable opposition from other interest groups, with different priorities, in the absence of a concerted effort to build coalitions that bundle multiple innovations together to solve the Kaldor-Hicks problem. And even then, misinformation and the raw exercise of political power can impede progress.

9.5.3 Example 3: The Irony of Bt Brinjal in South Asia

The case of Bt eggplant (also known as aubergine and in South Asia as *brinjal*) in Bangladesh and India brings the political economy of AFS innovation into especially stark relief.[12] Eggplant cultivation is widespread in south Asia, but very vulnerable to the eggplant fruit and shoot borer (EFSB), a pest previously controlled only with multiple applications of expensive and toxic chemical pesticides. Decades of conventional plant breeding had failed to promote adequate EFSB resistance in brinjal. Starting in 2000, scientists with the Indian seed company Maharashtra Hybrid Seeds Company (Mahyco) drew on prior transgenic scientific advances in introducing an insecticidal protein from the soil bacterium *Bacillus thuringeiensis* (Bt) into brinjal. Bt had been successfully introduced into cotton, maize, and other crops similarly vulnerable to borers and the protein is widely used in organic biopesticides. But the Bt brinjal variety is expressly transgenic, just like golden rice.

Transgenic crops require a range of regulatory approvals, including a national biosafety framework. India's approval process involves multiple stages of review, ultimately under the authority of the Minister of Environment and Forests (MEF). India's Genetic Engineering Appraisal Committee (GEAC) had previously

[12] This content draws heavily on informal conversations with experts such as Maricelis Acevedo, Ron Herring, Vijay Paranjape, Tony Shelton, and Usha Barwale Zehr, and on key studies such as Herring (2015), Herring and Paarlberg (2016), Shelton et al. (2018), Brookes and Barfoot (2020a, b), Ahmed et al. (2021) and Shelton (2021). Any errors are entirely mine.

approved Bt cotton for cultivation, yield gains from which led India to become the world's leading cotton exporter, and in October 2009, GEAC approved Bt brinjal for cultivation in India. A formal expert committee reviewed Mahyco's extensive field trials data and concluded that Bt brinjal was both safe and beneficial, as well as likely profitable for small farmers. But anti-GM groups objected vehemently and mobilized India's MEF to overrule GEAC and in February 2010 impose a moratorium on the cultivation of Bt brinjal in India, which remains current today.

It is notable that anti-GM activists prevailed in stopping Bt brinjal when they had failed to stop or rescind approval of Bt cotton. Cotton farmers have long been better organized in India, in part due to the necessity of commercializing fiber harvests, where a large share of perishable brinjal production is auto-consumed by farmers' own families or informally sold locally rather than through formalized marketing channels that feed national and global markets. Cotton exports are strategically important for India's economy, while brinjal is not. The national network of cotton agro-input dealers likewise banded together with farmers and Mahyco to support Bt cotton because the improved cotton seed is relatively profitable for input wholesalers and retailers, even with reduced pesticide sales, due in part to the large volume of seed sales. And Bt cotton was extremely profitable for farmers, so regulators could scarcely contain the spread of the seed even if they had wanted to. By contrast, the commercial incentives for dealer networks were less clear in the case of Bt brinjal, where reductions in pesticide sales were expected to largely offset any gains from the sale of improved seed. Furthermore, the Knightian uncertainty of possible health effects of transgenic food—as distinct from fibers—induced natural conservatism among many groups that further empowered opposition to Bt brinjal relative to the opposition Bt cotton faced. Environmental groups' repeated invocation of the precautionary principle further inflamed that inherent conservativism. As explained earlier, Knightian uncertainty and the precautionary principle leave innovations especially vulnerable to misinformation, of which there has been much concerning Bt crops (Lynas 2018). And because the scale of brinjal production by farmers was typically much smaller than that of cotton, the marginal farm profits at stake were likewise smaller. Cumulatively, while the scientific evidence in favor of Bt brinjal was strong, the politics of opposition were stronger in India.

Meanwhile, Bangladesh, unlike India, had no prior experience with cultivation of transgenic crops. But the favorable field trials evidence—over multiple consecutive years, as had taken place previously in India—convinced the Bangladesh Minister of Agriculture to actively pursue approval of Bt brinjal. Environmental activists were far less well organized and less influential in Bangladesh than in India, and in Bangladesh, the Minister of Agriculture had actively cultivated the support of the Prime Minister. Where India is a major exporter of pesticides, Bangladesh is a large pesticides importer, so the pesticide reductions expected from release of Bt brinjal could save considerable scarce foreign exchange for the country, eliciting support from the Minister of Finance. And the Minister of Environment was satisfied through inclusion of mandatory labeling of Bt brinjal seed packages. Building a coalition of the powerful and bundling in some arguably unnecessary accommodations—e.g., labeling—made a difference. The Bangladesh government approved cultivation of Bt brinjal in October 2013.

Astute readers might wonder why the intellectual property (IP) thickets that partly impeded golden rice's release did not obstruct Bt brinjal. The answer is that Monsanto owned—or already held valid licenses to use—the relevant IP around transgenic Bt crops and also owned a minority stake in Mahyco, the Indian seed company that first developed the variety. So IP issues that often prove problematic with technological innovations today were solved from the outset through commercial and legal agreements.[13]

Rigorous evidence on the impacts of Bt brinjal adoption clearly point to large economic, environmental, and health gains arising from improved yields and sharply reduced applications of toxic pesticides (Brookes and Barfoot 2020a, b; Ahmed et al. 2021). So why was Bt brinjal accepted and diffused broadly in Bangladesh, with favorable agronomic, economic, and environmental impacts, while it failed to secure approval in India, the country in and for which it was originally developed? The answer is clearly politics. In Bangladesh, multiple interests coalesced and bundled multiple innovations (a new seed, labeling) to create a coalition with especially powerful members to prevail against opposition that drew power from the inherent conservativism many have toward new technologies and misinformation that can feed that opposition. The structural situation in India was different, where the logic of collective action enabled a motivated minority of environmental activists, aided by a steady stream of (mis)information, to prevail over the more diffuse interests of millions of brinjal farmers and consumers. In India, the necessary coalitions failed to get built and Bt brinjal remains sidelined, cultivated widely, but illegally to this day.

9.6 Conclusion

Realizing the widely espoused goal of accelerating AFS transformation requires paying at least as much attention to human relationships and to the political economy of coalition formation as it does to sound science. Science can help us identify feasible, impactful innovations, be they technological, institutional, or cultural. But no one-size-fits-all solutions exist; no single innovation will solve the myriad problems confronting the world's AFSs now and into the foreseeable future. Indeed, no innovations exist that do not directly or indirectly pose risks to at least

[13] The IP around the technology was nonetheless contested legally when Mahyco and Monsanto were accused of biopiracy for using local brinjal varieties (Peschard and Randeria 2020).

some subpopulations or desired outcomes. For multiple reasons, but especially to overcome the collective action problems inherent to AFS transformation, it is imperative to bundle socio-technical innovations. That is a fundamentally human, and thus political, process.

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