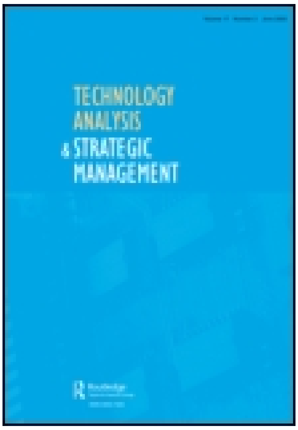

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Legacy sectors: barriers to global innovation in agriculture and energy

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Legacy sectors: barriers to global innovation in agriculture and energy

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The US national innovation system has a dual structure: part suited to rapid innovation, and part stubbornly resistant to change. The complex, established 'Legacy sectors' that resist change, particularly disruptive innovation, share common features that obstruct the market launch of innovations, over and above the 'valley of death' and other obstacles that have been the traditional focus of innovation policy. Innovations in Legacy sectors must penetrate a well-established and well-defended technological/economic/political/social paradigm that favours existing technology, characterised by (1) 'perverse' subsidies and price structures that create a mismatch between the incentives of producers and broader social goals, such as environmental sustainability, public health and safety, and geopolitical security; (2) established infrastructure and institutional architecture that imposes regulatory hurdles or other disadvantages to new entrants (3) market imperfections beyond those faced by other innovations: network economies, lumpiness, economies of scale, split incentives, needs for collective action, and transaction costs (4) politically powerful vested interests, reinforced by public support, that defend the paradigm and resist innovations that threaten their business models (5) public habits and expectations attuned to existing technology and (6) an established knowledge and human resources structure adapted to its needs. Beyond these obstacles, more socially desirable technologies that are driven by environmental or other non-market considerations must overcome the lack of agreed replacement standards against which putative alternatives can be judged. We have developed a new, integrative analytic framework for categorising the obstacles to market launch faced by Legacy sectors, and earlier applied this method to energy, health delivery, the long-distance electric grid, building, and air transport. In energy especially, the requirement for innovation is sufficiently urgent that large-scale domestic and collaborative international research should take place even at the cost of possible competitive disadvantage and even if it is some time before the USA adopts carbon charges and thereby puts pressure on the prevailing paradigm of fossil fuel use. We now extend this method to sustainable agriculture. American paradigms in agriculture and in energy are exported worldwide, delaying the development and spread of needed innovations that are not consistent with them. Foreign manufacturers wishing to enter US markets must suit their products in these sectors to American paradigms, while American exports of technology may be insufficiently cost conscious or respectful of environmental sustainability. Developing countries are technology takers and suffer from asymmetric innovative capability. They need to choose sources of technology best suited to their situation. India and China constitute new competitive threats, but also represent 'innovative developing countries' that have large domestic markets in which they are launching innovations aimed at their lower income populations.

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1. Introduction

In the most innovative society in the world, why are certain parts of the economy – like the health delivery system and the electrical distribution grid – stubbornly resistant to innovation (Weiss and Bonvillian 2011)?[1] Why is it hard to launch sustainable innovations in energy, health delivery systems, buildings, and agriculture at a scale sufficient for substantial impact? In short, why does the USA have what amounts to a dual economy: breathtakingly rapid innovation, capable of disrupting long-established practice and structures in the information, medicines, industrial agriculture, and military and aerospace industries – at the same time that other, equally important parts of its economy successfully resist disruptive innovations that would address broad environmental, security and public health goals?

These questions highlight an important gap in the American literature on innovation, which is focused largely on the 'valley of death' and other problems facing radical innovations that introduce new functionality, but which does not address the interlocking obstacles encountered in the disparate, disruption-resistant, complex established 'Legacy' sectors (Legacy sectors) cited in the preceding paragraph. These Legacy sectors share common features that, taken together, define a technological/economic/political/social paradigm that enables them to resist fundamental change (Freeman and Perez 1988; Perez 2002; Weiss and Bonvillian 2009, 2011).[2] The resulting market forces lead to the evolution of dominant designs for products that embody or are consistent with that paradigm, leading to technology '*lock-in*' that further reinforces the resistance to technological alternatives (e.g. Arthur 1989; Utterback 1979).[3]

These paradigms have implications beyond America's borders. First, they set limits on the ability of other countries to develop and launch desirable innovations in these sectors, since their efforts to penetrate some of their biggest potential markets for these products will be hamstrung by deeply entrenched obstacles. Second, most developing countries lack the technological and innovative capacity to strike out in fundamentally new directions, so that they largely accept the direction of innovation charted by technologically advanced countries and adapt the resulting innovations to their needs. This process occasionally produces remarkable results, as in the case of mobile finance in Africa and the application of biotechnology to problems of tropical medicine and agriculture. It has, however, delayed essential innovations in sustainable agriculture, energy conservation and other areas of great importance to developing countries. The rise of India and China as 'innovative developing countries' with a substantial and growing middle class, together with the technologies spawned by the revolution in information technology, create the possibility of more inclusive patterns of innovation (Kaplinsky et al. 2009, 177–97).

2. Paradigms inhibiting innovation in complex established legacy sectors

In our previous work, we used a new analytic framework to explain how technological/political/economic paradigms in complex, established Legacy sectors in the USA create major barriers to desirable technological innovations. They do so by enforcing and perpetuating a mismatch between broader social goals, such as environment and security, on the one hand, and the incentives of producers and consumers, on the other. In this paper, we expand the framework used in our previous publications to encompass international markets for technology and innovation, and to relate our framework to those used by other innovation researchers, specifically business-oriented researchers exploring disruptive technology[4] and science, technology, and society researchers exploring the properties of socio-technical systems (e.g. Christensen 1997, Christensen, Grossman, and Huang 2009; Sorensen 2002).

We then explore the properties of domestic Legacy sector paradigms in the agricultural and energy sectors, and expand the discussion to international markets in order to show how asymmetries in innovative capacity result in the export of these paradigms to developing countries and hinder the development and flow of technologies that could make important contributions to global social, environmental, and security problems. In agriculture, these barriers to desirable innovation are exacerbated by tariff regimes and other imperfections in global markets that inhibit overall investment in the sector, deny tropical countries their natural comparative advantage, and in this way inhibit their overall economic and social development (Johnson 1991).

We begin by defining the common features of these paradigms, expanding the definition to take into account the social dimension of the paradigm. We add new elements of the definition to those enumerated in previous papers: knowledge and human resources, value network (industrial structure), and the habits and expectations of consumers and users. This makes our definition of a technological/socio/economic/political paradigm [now with the addition of the prefix 'socio'] more nearly equivalent to the definition of a socio-technological system, with the difference that we drill much more deeply into the role of economics, policy and regulations, and the politics that underlie them. These common features, as identified by Weiss and Bonvillian (2011), are[5]

(1) '*Perverse*' *subsidies and price structures* favourable to existing technologies that create a mismatch between the incentives of producers and innovators and the goals of the larger society (Myers and Kent 2001).[6] These include the numerous subsidies to fossil fuels, the regulated electric power tariffs that discourage investment in the electricity distribution network, the sales-oriented profit structure of electric utility companies, and the procedure-oriented fee structure used by doctors and hospitals (Weiss and Bonvillian 2009, 41).
(2) A *government institutional architecture* that favours existing technology or discourages new entrants, accompanied by government support to infrastructure adapted to the requirements of existing technology. Here we distinguish the institutional or regulatory structure from the substantive content of the regulations themselves, which we discuss below. Examples include the balkanised or overlapping regulatory structures that affect the installation of large-scale solar and wind power installations, all of which require multiple approvals from separate jurisdictions for the installation of high-voltage power lines to connect them to the main electric power distribution grid. Other examples include the federal highway construction trust fund that historically promoted highways over mass transit investment, and the government-financed R&D system for natural gas extraction (Gas Technology Institute, n.d.). Institutional architecture can also give rise to regulatory barriers to innovation, as discussed below. On the other hand, government institutional arrangements can also promote new entry (for example, the strong history of the Defense Advanced Research Projects Agency (DARPA) in promoting technology advance) (e.g. Bonvillian 2009).
(3) *Well-established and politically powerful vested interests* that resist the introduction of technologies that threaten their business models. These include oil, coal, and natural gas companies in energy, health insurance companies, hospitals and medical associations in health delivery, and state regulatory agencies in the utility industry.
(4) *Market imperfections* that reinforce the position of existing technologies. These include network economies, lumpiness (large minimum required size) of investments, split incentives,

and requirements for collective action. These will be explored in more detail in the next section of this paper.

(5) *Public habits and expectations* attuned to existing price structures, dominant products and technology that underpin popular support to the policies and public expenditures favourable to existing technology. These include public expectations of cheap and convenient energy, widespread satisfaction with existing health delivery options (for those who receive adequate care and do not have to pay for it), and public reluctance to pay higher prices for energy-efficient buildings.

(6) An *established knowledge and human resources structure*: educational curricula, career paths and professional standards in medical, legal, and other technical fields that are adapted to the needs of existing technology.

These paradigms directly affect the speed and direction of innovation in the American industries to which they apply. Despite the very real obstacles that they face, innovations that reinforce these paradigms, or are at least compatible with them, are often successful, and indeed constitute the basis for much of the USA's comparative advantage in bio-pharmaceuticals, and fossil fuel, agricultural, military and aerospace technology. Even in Legacy sectors, technologies like light-emitting diodes and off-grid wind and solar energy have been successfully launched into niche markets from which they can expand and perhaps challenge established competitors. In contrast, paradigms in these Legacy sectors inhibit the development, the market launch and the implementation at scale of technologies that do not fit neatly into them, such as those for renewable energy, energy conservation, sustainable agriculture, and the 'smart' grid for the distribution of electric power in the USA.

The features of Legacy sectors cited above often occur in combinations that reinforce each other. For example, the private broadcast information industry has been particularly prone to disruption resistance at different stages of its evolution, often by means of market imperfections reinforced by government institutions and regulations for which the industry itself had lobbied. In radio and television, for example, the dominant industry developed the potentially disruptive successor technology but used intellectual property (IP) weapons and methods to which we have already referred to suppress it, sometimes for decades, because it threatened its business model. In two significant examples, television was thought to have the potential to destroy radio; and FM broadcasting required less power than AM and would have made possible many small stations that could have challenged the dominant handful of big networks, delaying the entry of both (Wu 2011).[7]

In some Legacy sectors, such as energy and developing country agriculture, innovation is further inhibited by a general under-investment in research and development, and in some cases, as in buildings and electric power distribution, by under-investment in or under-capitalisation of the sector as a whole. As we shall see later in this paper, these paradigms also impose obstacles for the development of technologies for many of the needs of developing countries that must depend on advanced countries for technologies that can be applied or adapted to their own particular needs.

3. Imperfections in technology markets

Of particular importance in our foundational work was the identification of imperfections in the market for technology that apply to specific industries, over and above the other paradigms that affect the innovative process as a whole (Weiss and Bonvillian 2011). We found that the need to achieve *network economies* was a particular barrier to the introduction of innovations based on information technology into the healthcare delivery system, whereas large minimum investment size (known to economists as 'lumpiness') was important to innovation in the pharmaceutical industry, whose business model depends on highly profitable 'blockbuster' drugs, and in the development of engineering-intensive technologies like carbon capture and sequestration and enhanced ('hot rocks') geothermal in the energy sector.

The imperfection of 'split incentives', in which the benefits of innovation go to someone other than the investor, is an obstacle to innovation in the application of information technology to both the 'smart' electric power distribution grid, in which the cost of investments in increased reliability cannot be readily passed on to consumers, and in the delivery of health services, in which the cost of investments in increased efficiency cannot be passed on to patients and insurance companies. This imperfection also applies to energy conservation technologies for buildings, where landlords are reluctant to make efficiency investments whose benefits they have historically not been able to recapture.

The need for *collective action* is a particularly important obstacle to innovation in the building industry, which is composed of numerous undercapitalised firms. It is also a factor in the commercial airline industry, which is also undercapitalised and which has benefited from innovation historically funded by the military budget, a pattern that has been undermined by the reduction in the procurement budget for military aircraft and the divergence between civilian and military aircraft performance requirements. As we shall see below, the need for collective action is also an important factor in innovation in agriculture.

The pattern of *government regulation* can also have a major impact on innovation. This is often influenced by *institutional structure* (Section 2, above), but is elaborated here because of its particular effects on technology markets. Regulation can protect incumbents from more innovative new entrants, as in the history of commercial aviation, trucking or telecommunication before deregulation efforts (e.g. Johnson 1995; Levine 1981; Robyn 1987). Alternatively, regulation can operate to encourage new technology entry, as with the acid rain provisions of the Clean Air Act Amendments of 1990 that encouraged, through a cap and trade system, new entry of SO_2 scrubber technology. In other words, regulation can either encourage or discourage innovation, depending on how it is structured and designed (Ellerman et al. 2000).

The socially desirable innovations needed to disrupt the paradigm of a Legacy technology often depend on environmental or other non-market considerations that are driven by government policy (as, for example, carbon charges) or by consumer willingness to pay extra (as, for example, organic produce or sustainably grown timber). Either of these drivers requires agreed external criteria that embody these values and can be the basis for an agreed replacement standard against which putative alternatives can be judged. These criteria and standards tend to be works-in-progress (examples include evidence-based medicine, 'smart' grid standards, and information technology standards for health services delivery) and are frequently contested (for example, low-carbon versus renewable energy technologies). This lack of standards adds to the usual problems that face all innovations, disruptive or not.

4. Exporting inappropriate paradigms

We now turn to the international dimension of our analytic framework, and to the concept that implicitly underlies the regime defined and enforced by the World Trade Organization (WTO) and by the Trade Related Aspects of Intellectual Property Rights (TRIPS) regime in areas other than agriculture. This regime constitutes the international analogue to the domestic quasi-free market defined in our previous publication (Weiss and Bonvillian 2011, 166ff).[8] This system is universally accepted among advanced industrial countries as the basis of the globalised knowledge economy and is enshrined in WTO and TRIPS.

Within the constraints of the WTO system, each sovereign country is entitled to evolve its own national innovation system and its own domestic paradigm. Any country may make investments in innovative capacity – defined broadly to include business climate, capital markets, connectivity and physical infrastructure, as well as support to research and development, scientific and technological services, and human resources – and consequent dynamic comparative advantage. Once a new product is developed, WTO rules make it difficult for other countries to restrict it from being imported, with largely theoretical exceptions for products deemed to have detrimental environmental or public health effects. The system of IP rewards innovation by protecting the resulting monopoly and the consequent economic rents of the innovator. The quasi-free international market in technology leads to an inherent conflict between IP rights, which are essential to encourage vital private investment in innovative technology, and needed global environmental, public health or other benefits associated with widespread implementation of many innovations in complex established Legacy sectors. This conflict admits of no clean universal solution, but must be addressed case by case. In agriculture, development assistance agencies, private foundations, non-governmental organisations, and even some multinational corporations have undertaken to make available innovative technology to farmers who otherwise could not afford them (ISAAA 2013). In infectious disease, major programmes of research and technical assistance have long been underway (Gates Foundation 2011). In energy, some programmes of international collaboration on technology implementation and to some extent on pre-competitive research are gradually taking shape (CEM, n.d.; ECPA 2013; GBEP 2013; International Renewable Energy Agency 2013; U.S. Department of Energy 2011a, 2011b; World Bank 2008a).

The impact of the quasi-free market on developing countries is mixed. The 'Gang of Four' (Korea, Singapore, Taiwan, and Hong Kong) made the necessary investments in dynamic comparative advantage during the 1970s and 1980s and these nations are competitive in the new knowledge economy. Likewise, China, India and perhaps Brazil and Mexico are on their way to becoming 'innovative developing countries' (Mashelkar 2008). Gulf States could, if they so choose, use their oil money to finance and benefit from innovation, especially given the continuing financial crisis in Europe and the USA. A few other developing countries – Thailand, Malaysia, Turkey and Chile, perhaps- are also within range. The 'Arab Spring' may revitalise science and technology in some North African countries (SciDevnet 2012). But the challenges for smaller and least developed countries (LDCs) are much more serious because markets and technology are moving so fast, and because some of the methods used by the Gang of Four are now forbidden by the WTO (although China evades WTO restrictions because of the allure of its huge market for foreign investors).

The result is *asymmetric innovative capacity*, in the sense that most developing countries are technology takers and have no choice but to accept technology from advanced countries and hence to import paradigms that evolved in advanced countries under quite different circumstances (Kaplinsky et al. 2009).[9] This works well if the needs of a developing country are the same as those of advanced countries, directly or with minor modifications, as, for example, in the case of middle-class banking services. Occasionally, as in the specific case of cell phones, developing countries have not only leapfrogged legacy landline technology but also built on imported technology to make world-class innovations in mobile finance to suit their own needs and situations. However, the export of paradigms from developed countries can also result in the importation of ill-suited technological patterns that inhibit innovation that might otherwise have been directed towards social objectives – high-tech hospitals rather than well-designed rural clinics, for example.

With important exceptions, developing countries have historically lacked sufficient technical and innovative capacity to strike out on their own to develop technologies not based on or adapted from models from advanced countries, or even to choose to import technologies from smaller exporters whose situation is closer to their own (a choice that may require resistance to political pressures and to temptations to corruption in public procurement).

The international technology market in developing countries (LDCs) involves important additional market imperfections. Capital goods specifically suited to conditions in developing countries require economies of scale in manufacture, which may be difficult to achieve if their market is scattered across many countries and if innovative firms in developing countries lack the expertise and infrastructure for worldwide marketing. Moreover, the combination of lack of market power and lack of technical and innovative capacity results in important areas of 'orphan technology' – technologies like malaria vaccine that would answer a critical social need, but that have no commercial market and are, therefore, dependent on public sector intervention by governments, private foundations, non-governmental organisations or development assistance agencies based in advanced countries.

The situation is brightened by a number of promising developments. The research arms of bilateral and multilateral assistance agencies, including the specialised agencies of the United Nations, have long sought to overcome these obstacles. More recently, their efforts have been complemented by new technologies and new actors. The revolution in information and communications technology has provided disruptive technologies in finance, education, health services delivery, small business creation and all aspects of logistics and coordination (Kaplinsky et al. 2009; Kaplinsky 2011).

The rise of India and China, which have large markets compared to those of other developing countries and the innovative capacity to develop products to satisfy them, has helped to create markets for efficient, low-cost products suited to the needs of poor people. The Nano automobile and the low-cost electrocardiograph are pioneering examples. The revolution in information and communications technology has provided a new vehicle for global marketing of products of all kinds (Aker and Mbiti 2010). A growing number of public–private partnerships are now aimed at orphan technologies at the 'bottom of the pyramid', especially in public health and education but also in raising the productivity of scattered small-scale producers (Prahalad 2006).[10]

Despite these positive developments, the obstacles to innovation in developing countries remain important. The combination of entrenched paradigms in Legacy sectors in advanced countries, asymmetric innovative capacity, lack of market power and assorted imperfections in domestic and international markets inhibits the development and spread of innovations that could make important contributions to global humanitarian, development and environmental problems. We explore these considerations as they apply to agriculture and energy, using our expanded analytic framework.

5. Industrial agriculture as a disruption-resistant legacy sector

The USA has a strong techno/economic/political/social paradigm for large-scale, mechanised, input-intensive industrial agriculture – big subsidies, strong vested interests, a well established value network, strong public expectations and habits, and a well-established knowledge structure – all of which reinforce the effects of the vast land and water resources and continent-sized market in favouring industrial, input-intensive agriculture (Pollan 2006; Roberts 2008).[11] The US Department of Agriculture (USDA) at the federal level has supported this model with subsidies, low-cost lending and price supports, research, development and extension programmes, and the educational and research functions of the land grant colleges that it helps support at the state level. This has helped overcome the problem of *collective action*, introduced in part II, facing the fragmented US agricultural sector, characterised as it is by a vast number of small, thinly capitalised, still largely family-owned farms.[12]

However, 'sustainable' agriculture – low-input agriculture that minimises environmental disruption and resource use and has largely been, to date, smaller in scale – generally has not directly benefitted from this paradigm. In addition to the weight of historical development favouring industrial agriculture, sustainable agriculture suffers from a number of intrinsic problems. First, sustainable agriculture is subject to many alternative definitions (USC; National Research Council 2010a).[13] Sustainable can incorporate 'organic' agriculture; generally speaking, organic can be characterised as defined and labelled 'practices that foster cycling of resources, promote ecological balance, and conserve biodiversity; synthetic fertilizers, sewage sludge, irradiation, and genetic engineering may not be used' (U.S. Department of Agriculture 2010). However, various standards for the definition of 'organic' agriculture disagree on whether any use of chemical pesticides, inorganic fertiliser, bovine growth hormone, or genetically modified (GM) crops is to be allowed. Other possible definitions would require free-range livestock, much more efficient water irrigation, minimum energy use, minimum environmental footprint, or local production that minimises transport between the sites of production and consumption (Merrigan and Lockeretz 2009). Second, although there certainly are signals this is changing,[14] sustainable agriculture in the USA did not benefit in the past from many of the services of the USDA and the land grant research system that together supply a scale of support that largely overcomes the collective action problem for American industrial farmers. On the contrary, most organic producers of whatever stripe have been small scale and ill-equipped to carry out research.

The result is that organic and sustainable farmers have been forced to establish themselves as an upscale, high-cost niche market. It is expanding rapidly from a low base, but despite the high hopes of its devotees, does not yet show clear signs of becoming a truly disruptive technology that can reach a scale to challenge the strongly entrenched, prevailing paradigm of high-input, large-scale industrial agriculture (Smith 2007). Indeed, the most promising sign that sustainable and organic agriculture may be 'mainstreamed' into the prevailing paradigm is its adoption by large-scale farmers – who in some cases achieve compliance with official organic standards by use of environmentally questionable, energy- or water-intensive technology (Rosenthal 2011).

The remarkable success of industrial agriculture, coupled with the Green Revolution, has been that it has scaled production to more than meet population growth;[15] continuing world population expansion and developing world industrialisation require food production gains at an accelerating pace indefinitely, reinforcing the dominance of input-intensive methods (Smil 2001). Even so, there are potential forcing mechanisms for a different kind of agriculture in the USA and other countries lurking in the wings. Water availability is a growing world problem, including in the USA; climate change may accelerate this shortage and disrupt current world food production patterns over time (Dahlman 2012).[16] The rise in energy costs provides another threat to the industrial scale of capital equipment and fertiliser production pervasive in US agriculture (U.S. Department of Agriculture 2013a).[17] In other words, limits on the heavy resource inputs required by industrial agriculture may force a different kind of resource balance in agriculture. There is thus the possibility that a more sustainable agriculture may in time disrupt the Legacy sectors in US agriculture and provide a source of technology better suited to the needs of developing countries as well, as discussed further in the following section (United Nations 2011).[18]

While the focus here is on the production of food crops, this production system is further embedded in a complex food system. The economic advantage in food is in value-added crops through processing and packaging foods. There is limited profit in produce that moves directly to grocery stores, but even greater price pressure on commodities that go into food manufacturing. The food system includes farms and their agricultural practices, processed food production, the international agricultural trading system, food transport and consumer health and nutrition delivery. The global interconnectedness of food processing can make the food system vulnerable, leading to increased food security risks due to shifts, for example, in the availability and price of fossil fuels for transport or unexpected weather patterns, with perverse subsidies that can disrupt markets and access, and with a notorious pesticide 'circle of poison' that can affect consumer health (Roberts 2008).[19] A global network of agricultural transport for processed as well as unprocessed food leads to tradeoffs between efficiency of transport and food quality, such as through plant breeding that delays ripening, but can reduce nutritional value, and the global spread of disease, usually bacterial, through increasingly efficient transport. Although our focus is on the production system for agricultural goods, this, in turn, is part of a larger and additionally complex food system that likewise has many of the properties of a Legacy sector.

6. The international market in agricultural technology

Turning now from the USA to the international picture, industrialised countries have their own systems of agricultural education, research and extension, and agricultural policies that define their own domestic paradigm, reflecting societies accustomed to cheap food and a well-established market system of processing and distribution of agricultural products. All advanced countries subsidise their agriculture in one way or another, in order to assure their populations cheap food and stimulate exports. Farmers and agribusiness, which are overrepresented politically in most advanced countries, heavily defend these subsidies, which are complemented by research, extension and other institutions that provide necessary innovative capacity and technical services.

Many small-scale farmers in developing countries, by contrast, practice organic agriculture by default, largely because they are too poor to afford industrial inputs such as fertiliser, pesticides, mechanised irrigation and heavy equipment. Many of these farmers would seek, if they were affordable, more such industrial inputs because in this way they could increase yields. Like farmers everywhere, farmers in developing countries suffer from *collective action* problems, but the institutions serving them are much weaker than those in advanced countries. Research and extension institutions are much less effective – an aspect of the *asymmetric innovative capacity* discussed earlier – and when they do exist are typically patterned on those of the advanced countries. Besides, technology for sustainable agriculture tends to be more locality specific than industrialised agriculture, and hence would put much heavier requirements on these researchers and extension workers for response to local conditions and hence for collaboration with farmers. Thus, higher yield but sustainable technologies appear somewhat elusive for the developing world.

This means that developing countries have limited opportunities to develop innovative, sustainable technologies that protect their environment, which by and large is more sensitive to unsustainable practices than that of temperate zones because of warmer temperatures and more fragile soils (McIntyre et al. 2009).[20] This situation is exacerbated by an overall under-investment in developing country agriculture and agricultural research, and by the imperfections in the global market for agricultural products – most especially by the subsidies to and protective tariffs around developed country agriculture that encourage dumping of surplus production into export markets (World Bank 2008b, Chaps. 6–7, 4). The well-known result of these subsidies is to reverse the classical comparative advantage in agriculture that should be enjoyed by tropical countries, and hence to depress investment in agriculture in these countries (Johnson 1991).

The upshot of this situation is that the input-intensive system of agriculture that characterises advanced country agriculture has been exported to the developing countries in modified form. The first stage of this paradigm export was the Green Revolution,[21] in which internationally supported research laboratories (that helped to overcome the problems of both *asymmetric innovative capacity* and the need for *collective action*) transferred and adapted technology for high-yielding varieties of cereal grains, including wheat and rice, based on selection and hybridisation techniques that were already in use in Japan and the USA (Conway 1998; Easterbrook 1997; Gaud 1968; Vietmeyer 2010, 2011). These crop development efforts to suit local production conditions were coupled with modern management efforts, irrigation techniques, synthetic fertilisers and pesticides and large-scale production of seed embodying higher yield, pest resistance and other desirable characteristics.

As with other forms of advanced country technology, this has resulted in major tangible benefits: greatly increased yields and much lower food prices initially in Mexico, Pakistan and India, then more broadly in Asia and Latin America than would otherwise have been the case. This arguably avoided the widespread starvation in India that had been authoritatively predicted, and may have saved a billion lives worldwide from starvation (Ehrlich 1969; Inter Academy Council 2004; Paddock and Paddock 1967; Vietmeyer 2011). At the same time, it put stresses on tropical environments in the form of erosion, chemical pollution and water stress that might have been avoided had there been more understanding of and attention to sustainability from the beginning (Conway 1998; National Research Council 2010a, Chap. 8).

The point here is not to offer criticisms of the Green Revolution, on which there is ample literature, but to point out that it was based on an advanced country paradigm, because the need to raise developing country yields in the light of increasing population was urgent and because no alternative, less input-intensive technology was available for transfer. Indeed, the use of fertiliser and pesticides in developing countries was so low in the 1950s that it was thought urgent at the time to increase them. The research and extension capabilities in Mexico, India, Philippines and many other developing countries increased dramatically, but the model was from the USA, Great Britain and France, reflecting their national agricultural paradigms.

The export of this paradigm has been further complicated by the recent impact on developing countries of three issues of foreign origin: the modest rise in food prices caused by competition for land use induced by subsidies to food crops, especially corn (Baffes and Haniotis 2010), the purchase of agricultural land in LDCs by public and private investors in wealthy, land- or water-short countries (Kugelman and Levenstein 2013; Minot 2011) and the export to developing countries of the largely European controversy over GM crops (Runge and Senauer 2007; National Research Council 2010b; Wedding and Turtle 2013). In the last case, European risk/benefit calculus – one perhaps appropriate to a region with ample food supplies – has been exported to countries where GM crops could make a major contribution to agricultural productivity (Gruskin 2012; Paarlberg, Borlaug, and Carter 2009).[22] This can be viewed as a *governmental regulation* market imperfection (Giddings et al. 2012).[23]

Critics point out quite correctly that existing GM crops benefit mostly large industrial farmers in advanced countries – but this is a matter of the choice of research objectives, itself a reflection of an entrenched paradigm. If researchers were tasked with, and given adequate resources for applying GM techniques to sustainable agriculture, the resulting technology could be quite different. Here the *lumpiness* of research on GM crops poses major obstacles to agricultural researchers in LDCs,[24] as the cost of a single commercial GM crop exceeds the entire budget of the Consultative Group on International Agricultural Research (CGIAR), the major network of international laboratories devoted to agricultural research for developing countries (CGIAR; Baum and Lejeune 1986).

The impact of IP protection on the availability of GM crops suited to the needs of developing country agriculture is more complicated. The Green Revolution, as noted above, was based on food crop varieties adapted by publicly funded international research laboratories from varieties developed by government and university laboratories in Japan, the USA and Europe, and placed by them in the public domain. The large commercial seed companies raised no objection to this system. Nor did governments raise objections to the international exchange of genetic material, which was correctly perceived to be of universal benefit. GM crops, in contrast, are developed by private companies and are subject to IP protection. Private foundations can facilitate the donation of these IP rights to developing country laboratories (e.g. ISAAA 2013; Nature Biotechnology 2012).[25]

There are, to be sure, possibilities for increased sustainability through a major shift within the prevailing paradigm of high-tech industrial agriculture, driven by disruption of traditional growing patterns due to climate change and by increasing global water shortages, as suggested in the previous section. Networks of low-cost sensors and radio frequency identification in plants and soil could enable far more efficient delivery of dosages of nutrients and water appropriate to particular plants and field areas.[26] Coupling drip irrigation techniques with a sensor system that delivers water based on the needs of different parts of fields could add significant conservation efficiency. Small-scale, semi-autonomous robotics responsive to field sensor networks could replace some of the current energy-intensive, large-scale mechanised equipment. Harvesting could occur when the network indicates particular plants are ready not on a fixed preset calendar date. Genomics-assisted plant breeding offers further technological options (Kingsbury 2009; Lusser et al. 2012; National Research Council 2012).

In agriculture as in energy, there is no single technological silver bullet; different geographic and climatic regions as well as nations will require differing approaches to agricultural conservation and technology. Any new agricultural technologies must still go through the cycle of research, development, prototyping, and test beds to demonstrate efficiencies and costs, and enable enough early deployment to drive down a cost curve so as to be competitive with industrial agriculture. The social features – the established knowledge system – of the existing paradigm require shifts in the focus of the US agriculture research and education system,[27] with a corresponding need for agricultural science expertise in the developing world (Grant 2009; McIntyre et al. 2009; National Research Council 2010a).[28] At the low end of the technological scale, agricultural researchers in developing countries are devoting increasing attention to the contributions of individual farmers to indigenous innovation through new methods of participatory research and extension (Reij and Waters-Bayer 2002). Even so, the problems of *collective action*, *split incentives*, *government regulation*, *lumpiness* and *the established knowledge system* in the legacy agricultural sectors of both the developed and developing world remain; until they can be overcome, such a transformation will remain elusive.

7. The international fossil fuel economy

Our previous publications set forth the characteristics of the technological/social/economic/political paradigm that underlies the fossil fuel-based energy economy in the USA and by extension on all advanced countries (Bonvillian and Weiss 2009, 289–300). In this paradigm, producer incentives are misaligned with the broader environmental need to conserve energy and minimise carbon dioxide emissions, as well as the geopolitical and economic need to minimise the importation of petroleum. Both of these social needs apply worldwide, in the sense that it is in everyone's interest that everyone else apply carbon-minimising and energy-conserving technology, no matter where on earth they live.

The quasi-free international market in energy technology thus leads to the tension, previously discussed, between the desire of innovators and innovating nations to realise the gains of IP rights, on the one hand, and global environmental and security externalities, on the other. IP rights are essential to encourage private investment in innovative energy and energy-using technology. On the other hand, the existence of global externalities implies that a free exchange of innovative technology would be desirable to encourage the implementation of technologies that minimise carbon dioxide emissions and petroleum imports (Weiss and Bonvillian 2011, Chap. 7).

At a minimum, these global externalities justify a substantial programme of international collaboration on pre-competitive research as well as in technology implementation, and in fact some efforts at such programmes are underway. Innovative crossover efforts are underway in countries that do not share the impediments of American paradigms, such as China, and feed-through tariffs and other policy instruments that encourage the use of renewable energy technologies in Germany and Spain, and the production financing by provincial Chinese governments for US-developed advances in energy technology that the USA is not prepared to implement at scale itself (Clean Air Task Force 2013; Asian Clean Energy Innovation Initiative 2013). While the USA may reasonably wish to benefit from its own innovations rather than shifting their market-creation gains to China, in effect these constitute pilot projects for technologies that could be potentially disruptive back in the USA should market imperfections and other obstacles somehow be removed (U.S. Department of Energy 2011a, 2011b). Either way, the implementation of these technologies would greatly benefit American consumers – although at the potential cost of competitive disadvantage of American producers. On the other hand, we cannot count on China or any other country to take up the slack in developing and launching technologies for which there is unlikely to be a near-term commercial market because of deeply entrenched obstacles in a global Legacy sectors paradigm.

The absence of carbon charges or other incentives for carbon-saving technology poses obstacles even at the stage of research collaboration, especially when large sums of money are involved, as is the case for demonstration projects of lumpy, engineering-intensive technologies like carbon capture and sequestration and enhanced ('hot rocks') geothermal (Stavins 2012). Firms and countries will likely slow the investment of billions of dollars and the time commitment of its best technical people in a risky technology that will be economic only if carbon charges come into widespread global use (Business Green 2011; Guardian Environment Network 2011; U.S. Department of Energy 2011).[29]

The situation is further complicated by the rise of China as a major manufacturer of hardware for renewable energy, and increasingly as a major investor in research and technology development in this and related areas (Breznitz and Murphee 2011; Breakthrough Institute and Information Technology and Innovation Foundation 2010, 23–4, 34–8, 48–52, 67–74; Dahlman 2012; Hargraves and Moir 2010; Kazimi 2003; Lewis 2013; Martin 2011; Pew Charitable Trusts 2010; Tan and Gang 2009). Efforts to launch collaborative research at the pre-competitive level have been hindered by the recession in advanced countries, and by the political complications associated with the rise of China as an economic and possible geopolitical competitor (Lewis 2010). It remains to be seen how these issues will play out in the context of specific individual collaboration projects.

8. Global implications of domestic paradigms

It is a standard observation in the study of the transfer of technology to developing countries that imported technology embodies cultural values essential to industrial modernisation: workforce discipline, acceptance and support of productivity gains, and understanding of the economic value of time. The older literature on 'appropriate technology' also frequently noted that such imported technology was typically developed to correspond to the factor endowments of developed countries, which it was frequently argued were inappropriate to developing countries (Kaplinsky 2011; Stewart 1977, 1981).

Neither literature, however, took explicit note of the fact that in some sectors at least, technology in advanced countries embodies less desirable characteristics: lack of cost consciousness, for example, and profligacy in the use of natural resources stemming from their having been treated economically as free goods. Technology in these sectors can result from paradigms that are resistant to change even though they do not take into account important social and environmental objectives in the exporting country, and, in effect, are 'inappropriate' to both the exporter and the recipient. Indeed, it is common to acknowledge this fact indirectly in the form of a wistful hope that the developing countries might avoid repeating the mistakes of the developed countries, and instead 'leapfrog' over legacy technologies and follow a more sustainable path. Continuing resource exploitation and the rapid growth of automobile markets in emerging nations are examples that suggest, however, that this may remain a hope rather than a reality.

With occasional exceptions – cell phones are the most prominent example – this hope by and large has not been fulfilled. As we have seen earlier, agricultural research in developing countries has historically focused on technologies requiring the increased application of fertiliser and pesticides (although to be sure, starting from a very low base), on the assumption that attention to environmental issues could be postponed (National Science Foundation 2006).[30] Energy policies in emerging nations have focused on increasing the supply of fossil-fuelled electricity, rather than on supplying energy in forms best suited to conservation and specific end-uses (Goldemberg, Johannson, Reddy, and Williams 1981). Builders in tropical countries have constructed 'modern', glass-walled, air-conditioned skyscrapers, even in desert countries with distinguished traditions of attractive, energy-conserving architecture.[31]

The reasons are not hard to find. First is the familiar problem of 'orphan technology' – technologies for which there is a need but no market. Poor countries and poor people do not offer large enough markets for products like malaria vaccines, which, therefore, depend on the benevolence of rich countries and private foundations (McNeil 2012). This is not a market failure. It is, after all, the way markets are supposed to work. They need enough customers with money to pay in order to allow products to be made at sufficient scale to be profitable.

But important imperfections in the international market for technology are also involved here. Developing countries have lacked the technical and corresponding innovative capacity – and perhaps more importantly, the institutional and political strength – to strike out in new directions, although some emerging economies have shown that it is possible to break out of this box. Importation of high-tech equipment makes for attractive photo-ops, and in addition is popular with exporting countries and their development assistance agencies – and not incidentally offers superior opportunities for corruption. 'Advanced', imported technologies have the prestige of the foreign, and have the extra advantage of having been shown to work in their countries of origin – a version of the *first mover advantage*. More generally, these nations point out, why should we take the chance of trying out a new approach, when we can follow a well-worn path blazed by the countries that have already developed? Why have we the responsibility to conserve resources for the benefit of humankind, they ask, when our predecessors in advanced countries have not done so?

The technological/economic/political/social paradigms in innovative countries thus have global as well as domestic implications. Technology trajectories in Legacy sectors whose origins lie in market imperfections peculiar to their country of origin may affect the choice of technology all over the world. This technological lock-in may be problematic not only because it limits access to new, more appropriate technology paradigms in developed nations, but may be even less appropriate to the differing needs of the developing world.

The dramatic rise of China and India creates new opportunities. These countries combine growing investments in research, development and innovation with large domestic markets that offer attractive commercial possibilities for products suited to the needs of the poor as well as those of a growing middle class (Dahlman 2012). For these countries, and especially for China as the world's leading manufacturing centre, 'orphan technology' is at least as much a commercial opportunity as a social problem. China especially is emerging as a formidable competitor, vigorously seeking markets for low-cost products in both advanced and developing countries, as well as for potentially disruptive products like equipment for generation of renewable energy (Steinfeld 2010).

From the developing country point of view, this may be a big advantage, as these new actors are likely to be major sources of technology aimed more at their lower income populations – technologies that have hitherto been 'orphaned' by the lack of a commercial market of paying customers (Kaplinsky et al. 2009). On the other hand, the world is in great need of innovative technology in complex, established Legacy sectors like agriculture and energy, where both the development and large-scale implementation of innovation is often stymied by entrenched paradigms that have been exported worldwide. Here developing countries need to build the capacity to identify technology that has been developed in countries unaffected by these strictures.

There are sustainability reasons for the USA and other advanced countries to engage in cooperative, pre-competitive research and technology implementation, in efforts to overcome established technological paradigms in areas like sustainable agriculture, renewable energy or infectious disease, where continued innovation serves everyone's interest. However, it is overly optimistic to expect that such international collaboration will overcome the many obstacles to widespread implementation of sustainable technologies in these and other complex, established Legacy sectors in the absence of substantial change in one or another underlying technological/economic/political/social paradigm. The question for the future is whether the US paradigm in these and other complex established Legacy sectors will be entrenched as a global paradigm and hence as a permanent obstacle to badly needed innovation, or whether disruptive innovations begun and tested in places free of these strictures will come to flourish.

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Notes

1. An early version of this article was posted in Atlanta Conference on Science and Innovation Policy. All URLs are up to date as of 22 October 2013.
2. The term 'techno-economic paradigm' has been used by growth economists Christopher Freeman and Carlotta Perez to refer to a far-reaching cluster of technologies that creates 'a new best practice frontier' with 'pervasive effects throughout the economy', giving rise to a 'great surge of development' that constitutes an innovation wave (or Kondratiev wave). We use the term somewhat differently to refer to the technologies, and the related political-economic-social systems built around them, that form an entrenched Legacy sector resistant to disruptive change.

Freeman and Perez were studying the innovations that do happen and we are studying innovations that do not, but the basic phenomena are much the same. The term paradigm itself goes back to Plato (Timaeus 28A), and was made prominent by Thomas Kuhn (1996), who defined a scientific paradigm as: 'universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of researchers'.

3. Here we distinguish between the dominant design of *products*, as defined by Utterback, from the larger paradigm that is the hallmark of the Legacy *sector*. The latter concept is in essence an extension of the former.
4. The definition of 'disruptive innovation', taken from the website of its originator Clayton Christensen, 'describes a process by which a product or service takes root initially in simple applications at the bottom of a market and then relentlessly moves up-market, eventually displacing established competitors'. As originally conceived, this process takes place entirely in the private sector. In his later work, Christensen broadened this concept to include a product or organisational framework (as, for example, the rationalisation of the hospital and indeed much of the healthcare system), whose introduction could lead to the rationalisation of an entire industry. The latter process often exceeds the capacity of the private sector acting alone and requires substantial changes in public policy.
5. The first four of these features are taken from Weiss and Bonvillian (2011). Numbers 5 and 6 are added in order to bring our definition closer to the definition of regime found in the literature on socio-technical systems, which emphasises the link between technology and social systems, especially in firms and other organisations. See, for example, Russell and Williams (2002, 128). Where our previous work emphasised the dimension of political economics, we now refer explicitly to the social dimension that underlies the politics that in turn often dictates the economics. In practice, all of these elements are intertwined.
6. For analytic purposes, we distinguish between pricing structures (how prices differ between purchasers of the same product, or among types of product for the same purchaser), on the one hand, and the change in the prices themselves due to subsidy.
7. Wu calls the results cited here the Kronos effect, after the mythical king that ate his children because they were predicted to overthrow him.
8. We refer to the market in which many innovations operate as 'quasi-free'; it is not completely free, not only because it is designed to provide economic rents to the innovator and is affected by market imperfections at the stage of market launch, but also because such innovation benefits from extensive government funding of early-stage research (which greatly exceeds private-sector expenditures at this stage), and major support to science and technical education.
9. This statement is a variant of the commonplace that technology embodies the economic factors and social values of the place where it was invented or commercialised, so that the importation of technology may either require an importation of these values or, alternatively, may be inappropriate to local conditions or factor proportions.
10. Prahalad, writing for a business school audience, emphasises profit-seeking initiatives of the private sector, but many of the examples he cites required intervention at some point by government, foundations, development assistance agencies or other institutions not motivated by profit.
11. Roberts argues that large-scale food production created paradoxes where high-volume factory food production systems created new risks for food-borne illness; high-yield crops generated grain, produce, and meat of declining nutritional quality; and where nearly a billion people are overweight and a similar number are hungry.
12. Although overall agricultural production is decentralised, there are centralised, large-scale agribusiness elements in the system, including major equipment producers, agricultural chemical firms, and commodities trading firms.
13. US agricultural law states that the term 'sustainable agriculture' means an integrated system of plant and animal production practices having a site-specific application that will, over the long-term—(A) satisfy human food and fiber needs; (B) enhance environmental quality and the natural resource base upon which the agriculture economy depends; (C) make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; (D) sustain the economic viability of farm operations; and (E) enhance the quality of life for farmers and society as a whole. (7 U.S.C. 3103, Sec. 19). See also the definition used by the U.S. Department of Agriculture (2013b) National Center for Appropriate Technology, National Sustainable Information Service (ATTRA) and the sources referenced therein. For research for small-scale farmers in sustainable agriculture, see also the Rodale Institute website, http://rodaleinstitute.org/new-farm
14. The USDA supports farmers, ranchers, organisations, businesses, consumers and others in improving agricultural sustainability through a number of activities and programs, including: the Sustainable Agriculture Research and Education (http://www.sare.org/); Alternative Farming Systems Information Center, National Agricultural Library (http://afsic.nal.usda.gov/nal_display/index.php?tax_level=1&info_center=2); Agricultural Research Service, National Sustainable Agriculture Information Service (ATTRA, https://attra.ncat.org/); National Agroforestry Center of the Forest Service and the Natural Resources Conservation Service (http://www.unl.edu/nac/); Cooperative State Research, Education and Extension Service, Sustainable Agriculture (http://www.csrees.usda.gov/nea/ag_systems/ag_systems.cfm and http://www.csrees.usda.gov/sustainableagriculture.cfm); Agricultural

Research Service National Program: Integrated Farming Systems (http://www.ars.usda.gov/research/programs/programs.htm?NP_CODE=207); Economic Research Service publication: Green Technologies for a More Sustainable Agriculture (http://www.ers.usda.gov/catalog/OneProductAtATime.asp?ARC=c&PDT=2&PID=46); and Direct Marketing, Agricultural Marketing Service, National Organic Program, Agricultural Marketing Service (http://www.ams.usda.gov/AMSv1.0/nop).

15. For example, the 1913 Haber-Bosch process that allowed large-scale chemical fertiliser production appears to have been a significant enabler of world population growth.
16. Dahlman points out that rapid industrialisation of emerging nations is placing significant strain on world environmental resources.
17. USDA is supporting adoption of renewable energy by US farmers in a number of programs (U.S. Department of Agriculture 2013).
18. Sustainable agriculture was emphasised at the June 2012 Rio + 20 meeting on sustainable development.
19. Certain controlled pesticides are barred from application but not production in the USA, and so are applied on crops abroad, which are imported back into the USA.
20. McIntyre (2009) is a comprehensive assessment of the state of agricultural technology in developing countries. The World Bank Independent Evaluation Group (2010) conducted a review of this assessment. The 2012 Annual Letter from Bill Gates (2012) of the Gates Foundation delineates the need for innovation in developing world farming as it faces the twin challenges of population growth (9.3 billion world population by 2050) and the disruptive effects of climate change.
21. The first use of the term was in a speech by W.S. Gaud, director of US Agency for International Development (1968).
22. Thawing environment for transgenic products outside of Europe partly reflects a realization that grain commodity prices are threatening food security and that, according to the UN, agricultural production will need to rise by 70% to meet the needs of the world's growing population.
23. 'Galvanizing plant science in Europe will depend on an overhaul of the tangle of indefensible regulations,' Giddings et al. (2012) regarding transgenic research that is key to plant breeding advances.
24. A similar lumpiness makes it uneconomic to develop commercial pesticides specific to 'minor' crops whose markets total 'only' a few billion dollars, forcing growers to use less effective and more environmentally harmful chemicals developed for other crops.
25. See, for example, work of the International Service for the Acquisition of Agri-biotech Applications. The example of golden rice is instructive. See http://www.goldenrice.org. This product was created by scientist Ingo Potrykus, genetically engineered from a gene introduced from daffodils to provide sufficient pro-vitamin A in rice to reduce the incidence of dietary-induced blindness; it was supported by the Rockefeller Foundation and is unencumbered by IP restrictions.
26. This approach reflects ongoing conceptual work by Prof. Sanjay E. Sarma, MIT.
27. The comparative lack of public investment in agriculture basic research (especially compared to the level of public investment in research related to health, as for example through the National Institutes of Health) and the lack of competition in the awarding of research grants has resulted in quite limited US technology new entry. The entrenched, non-competitive entitlement system for allocating research funding to established agriculture schools has been supplemented by the competitive grant awards from NIFA embracing more advanced biology advances; these reforms could be accelerated (Stokstad 2010).
28. This report applies an Agricultural Knowledge, Science, and Technology (AKST) framework and argues that "Scientific and technological knowledge and information can (1) add value to resources, skill, knowledge, and processes, and (2) create entirely novel strategies, processes, and products . . . . The creation of favorable conditions making it possible for different actors to engage in collaborative learning processes – i.e., the increase in space and capacity for innovativeness – has thus gained prime importance. Approaches based on linear understandings of research-to-extension-to application are being replaced by approaches focusing on processes of communication, mutual deliberation, and iterative collective learning and action" (National Research Council 2009).
29. This pattern is already visible. Although Department of Energy efforts to undertake carbon sequestration demonstrations began in 2003, the program was subsequently reorganised into seven regional partnerships; only one of seven regional partnerships has reached the stage of injecting CO_2 for geological storage.
30. National Science Foundation's (NSF) BREAD program of global agricultural research, a partnership with the Gates Foundation through NSF's Plant Genome program, may prove an exception in agriculture to this pattern.
31. The energy-conserving traditions of Arab agriculture are to be showcased in Abu Dhabi's eco-city of Masdar.

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