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Article

The Theory and Practice of Genetically Engineered Crops and Agricultural Sustainability

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Abstract: The development of genetically engineered (GE) crops has focused predominantly on enhancing conventional pest control approaches. Scientific assessments show that these GE crops generally deliver significant economic and some environmental benefits over their conventional crop alternatives. However, emerging evidence indicates that current GE crops will not foster sustainable cropping systems unless the negative environmental and social feedback effects are properly addressed. Moreover, GE crop innovations that promote more sustainable agricultural systems will receive underinvestment by seed and chemical companies that must understandably focus on private returns for major crops. Opportunities to promote crops that convey multi-faceted benefits for the environment and the poor are foundational to a sustainable food system and should not be neglected because they also represent global public goods. In this paper, we develop a set of criteria that can guide the development of GE crops consistent with contemporary sustainable agriculture theory and practice. Based on those principles, we offer policy options and recommendations for reforming public and private R&D and commercialization processes to further the potential contributions of GE crops to sustainable agriculture. Two strategies that would help achieve this goal would be to restore the centrality of the public sector in agricultural R&D and to open the technology development process to more democratic participation by farmers and other stakeholders.

Keywords: genetic engineering; sustainable agriculture; social impacts; democratic participation

1. Introduction

According to their proponents, genetically-engineered (GE) crops foster agricultural sustainability by boosting economic performance and addressing key environmental challenges facing adopting farmers [1,2]. Some scholars even argue that GE crops should become an option within organic agricultural systems [3]. Yet, many critics contend that current GE crops are an anathema to sustainable agricultural approaches because they are single interventions rather than one element in a systems approach, and perpetuate a heavy reliance on off-farm synthetic inputs, a strategy that is believed to impose long-term ecological and economic risks [4]. From our perspective, these vociferous proponents and critics of GE agricultural technology share a strong technological deterministic orientation. Technological determinism refers to the idea that a technology's influence on society is unidirectional and guided by qualities inherent to the technology, rather than being shaped by political, economic, and social contexts [5]. Such an orientation fails to appreciate how social structures and processes of technological development are embedded within each other, and subsequently do not represent accurate evaluations of a technology's sustainability potential. We challenge this deterministic orientation by presenting a comprehensive set of criteria that can be used to assess the sustainability of current GE crop usage and to help guide a process of technology R&D that fosters agricultural sustainability.

This deterministic view of the R&D process will also hinder the degree to which non-GE technologies foster more sustainable agriculture approaches. As we argue below, that degree depends largely on the extent to which farmer and other stakeholder input is integrated into all stages of the R&D process. In the case of GE crops, the increasing concentration of industry and control of related intellectual property likely has limited broad stakeholder input into developed products. Furthermore, the small amount of resources for public GE crop research, which traditionally has been more open to such input, has not proven an effective counterweight to the strong private control. If these same patterns pertain to non-GE crop R&D, our thesis maintains that the potential of new technologies to advance progress on sustainable agriculture will also be limited.

For both scientific and economic reasons, the first generation of GE crops has largely focused on improving the efficacy of weed and insect control. Bioscientists had the technical capacity to make these first transformations relatively easily, and the demand for pest control by farmers was robust. Economically, the narrow emphasis of early GE crops was an understandable approach by commercial interests who wished to achieve acceptable market rates of return on their investments. However, the concept of sustainability is not limited to a simple consideration of technical and/or commercial economic interests. As we will argue, continued reliance on the current GE crop development strategy will not provide the full range of opportunities to exploit the potential of GE crops for enhancing sustainable agricultural development.

To develop our argument, we first review contemporary theories of agricultural sustainability to discern the central operative goals for such systems. This exercise gives us the foundation for articulating in Section two a set of criteria that, if applied, would maximize the potential of GE crops to foster the development and application of such technologies to advance agricultural sustainability. In Section three, we briefly review the status, accomplishments and challenges for the first generation of GE crops that has been aimed principally at pest control. Then, in Section four, we analyze the current generation of GE crops for their conformance to the goals and criteria for sustainable agriculture. Section five draws conclusions from the analysis and offers policy options to innovate GE crops that contribute to those goals and criteria.

Our analysis demonstrates that the research, development and commercialization processes associated with GE technology must be reformed to address the full spectrum of sustainability dimensions. We conclude by offering policy options that could advance progress toward that goal. In doing so, we explicate the neglected social and human dimensions to the technology, including equity effects and the failure to address certain institutional issues. This analysis builds off of a recent report by the National Research Council on GE crops and farm sustainability in the U.S., follow-on papers to that report by Ervin, Glenna and Jussaume and Ervin and Welsh, and a new National Research Council report on moving toward sustainable agricultural systems in the 21st century [6-9].

2. Sustainable Agriculture Goals

To explore the potential of GE crops to advance sustainable agriculture, we must start by defining, and identifying the dimensions of, sustainable agriculture. This presents challenges because, what constitutes “sustainable agriculture” remains contested in both academic and policy-making circles. One of the most cited definitions of agricultural sustainability is the one used by the U.S. Department of Agriculture, which was codified into law in the 1990 Food, Agriculture, Conservation and Trade Act. Under that statute, the term “sustainable agriculture” means an *integrated* (our emphasis) system of plant and animal production practices having a site-specific application that will, over the long term:

- “satisfy human food and fiber needs
- enhance environmental quality and the natural resource base upon which the agricultural economy depends
- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls
- sustain the economic viability of farm operations
- enhance the quality of life for farmers and society as a whole ” [10].
- To more fully appreciate the complexity, and more significantly the holistic, integrated nature, of definitions of sustainable agriculture, it is informative to recognize how this concept developed historically in contradistinction to conventional industrial agriculture. Harwood has argued that the sustainability movement in agriculture emerged and grew throughout the 1900s

alongside of agricultural industrialization [11]. He locates a divide between the "systematic agriculturalists", who supported the industrialization model, and the "scientific agriculturalists," who sought to work with nature as natural historians. For Harwood, the key difference in these two approaches to agriculture lies in reductionism *versus* holism [11]. The biodynamic principles that emerged from the scientific agriculturalist movement included "diversification, recycling, avoiding chemicals, decentralized production and distribution…" ([11], p. 7), He highlights three basic principles of sustainable agriculture:

- "The interrelatedness of all parts of a farming system, including the farmer and his (sic) family.
- The importance of the many biological balances in the system.
- The need to maximize desired biological relationships in the system and to minimize use of material and practices that disrupt those relationships" ([11], p. 12).

Harwood explains how these principles have been converted into a plan for action:

- "Agriculture must be increasingly productive and efficient in resource use.
- Biological processes within agricultural systems must be much more controlled from within (rather than by external inputs of pesticides).
- Nutrient cycles within the farm must be much more closed" ([11], p. 15).

As was common in early analyses of sustainable agriculture, Harwood focuses predominantly on the ecological, and not on the social and economic dimensions, of an integrated agricultural system.

- Following a similar approach of distinguishing between conventional industrial agriculture and sustainable agriculture, Lyson expands upon Harwood's explanation and argues that the emergence of agricultural biotechnology and GE crops highlights the divide between two radically-opposed socioeconomic and biological paradigms [4]. He contends that the conventional agricultural paradigm combines the reductionist approaches of experimental biology and neoclassical economics as it strives to maximize productivity and efficiency. In such a paradigm, he argues, the role of those who work the land and handle the food is reduced for the most part to the role of "inputs." In the contrasting paradigm, "sustainable agriculture denotes a holistic, systems-oriented approach to farming that focuses on the interrelationships of social, economic, and environmental processes" ([4], p. 195). In this paradigm, interrelationships between people, and between people and nature, are all emphasized. Lyson further argues that biotechnology (at least in its current formation) fits squarely within the reductionist paradigm and is, therefore, incompatible with sustainability [4].

The more holistic view of sustainable agriculture is reflected in the National Research Council's recent definition of sustainable agriculture, which is a modification of previous Farm Bill definitions [9]. The NRC panel argues that "…improving sustainability is a process that moves farming systems along a trajectory toward meeting various socially determined sustainability goals as opposed to achieving any particular end state". Agricultural sustainability is defined by four generally agreed upon goals:

- Satisfy human food, feed, and fiber needs, and contribute to biofuel needs.
- Enhance environmental quality and the resource base.

• Sustain the economic viability of agriculture.
• Enhance the quality of life for farmers, farm workers, and society as a whole." ([9], p. 23).

This definition is consistent with the United Nation's Food and Agriculture Organization's characterization of sustainable agriculture and rural development as a systems approach that:

- "Ensures that the basic nutritional requirements of present and future generations, qualitatively and quantitatively, are met while providing a number of other agricultural products.
- Provides durable employment, sufficient income, and decent living and working conditions for all those engaged in agricultural production.
- Maintains and, where possible, enhances the productive capacity of the natural resource base as a whole, and the regenerative capacity of renewable resources, without disrupting the functioning of basic ecological cycles and natural balances, destroying the socio-cultural attributes of rural communities, or causing contamination of the environment.
- Reduces the vulnerability of the agricultural sector to adverse natural and socio-economic factors and other risks, and strengthens self-reliance" ([12], p. 14).

What these definitions share is the recognition that for agriculture to be sustainable it must necessarily incorporate an understanding of the interaction of social, economic and ecological dimensions of the production process. They also recognize that sustainability cannot be achieved by focusing on short-term benefits or through the privatization of benefits and the socialization of risks. Rather, if new technological advances are to achieve sustainability, it is imperative to understand how a technology can advance various aspects of ecological health in a manner that simultaneously ensures economic and social well-being for broad segments of the population, and for future generations. It is this holistic conceptualization of sustainability that we use to assess current and potential advances in GE technology. The same framework should apply to non-GE crop and other agricultural technologies.

While the overall approach to sustainability appears to be universal, the content of sustainable agriculture varies across countries. Aerni found that the priority elements of sustainable agriculture for Switzerland and New Zealand varied based on key stakeholders views in each country [13]. The Swiss do not view international trade and new technologies favorably, while the New Zealanders strongly endorsed economic and technological change as central in pursuing sustainable agriculture. As we will argue, this diversity of approaches to sustainable agriculture reinforce the importance of the fundamental role of inclusive stakeholder participation in understanding sustainability and thus defining the potential role of agricultural biotechnology in promoting sustainability. A main challenge is to assure that no single or select interest groups gain disproportionate influence over the sustainability agenda, and thereby privatize the public trust [13].

3. GE Crop Growth and Impacts

The use of GE crops has exploded over the last decade in countries that have approved their use. Highlights from a comprehensive inventory of GE crop use in 2009 around the globe include:

- "Small and large farmers in 25 countries planted 134 million hectares (330 million acres) in 2009, an increase of 7 percent or 9 million hectares (22 million acres) over 2008.

- In 2009, the number of biotech farmers worldwide increased by .07 million to 14.0 million, 90% of those were small and resource-poor farmers in developing countries.
- For the first time, biotech soybean occupied more than three-quarters of the 90 million hectares of soybean globally, biotech cotton almost half of the 33 million hectares of global cotton, biotech maize over one-quarter of the 158 million hectares of global maize and biotech canola more than one-fifth of the 31 million hectares of global canola.
- Developing countries increased their share of global biotech crops to almost 50% in 2009, and are expected to increase biotech hectarage in the future.
- In 2009, Brazil narrowly displaced Argentina to become the second largest grower of biotech crops globally.
- While 25 countries planted commercialized biotech crops in 2009, an additional 32 countries, totaling 57, have granted regulatory approvals for biotech crops for import for food and feed use and release into the environment since 1996" ([14], no page numbers).

According to this source, the 134 million hectares of biotech crops planted in 2009 represents the "fastest adopted" modern crop technology in human history, with an 80-fold increase from 1996 to 2009 [14]. The recent NRC assessment concluded that rapid adoption of GE crop technology in the United States supports the interpretation that the first generation of GE soybean, cotton and maize varieties presented many U.S. farmers with economically attractive pest control technologies compared to conventional crop varieties [6].

Within this context, it is important to note that only a few traits on a small number of crops have been genetically engineered since the first GE crop was commercialized in 1996. In the United States, for example, the vast majority of those crops have focused on two characteristics; herbicide resistance (HR) and insect resistance (IR). The crops with these characteristics have become widespread across many regions, but not uniformly so [6]. HR, IR and combinations (stacks) of the two dominant GE traits were used on 80–92 percent of acres planted to soybean, cotton and corn in 2008 in the U.S. This accounts for approximately half of all cropland planted in the country, but the three crops account for a very small minority of the number of commercial agricultural commodities grown in the United States.

This narrowness in the scope of GE crop development is also reflected in the debates surrounding the sustainability impacts of GE crops, wherein proponents and critics alike have marshaled evidence to support their positions [2,15]. Unfortunately, both sides generally omit certain aspects of the sustainability concept. The NRC assessment represents a comprehensive and dispassionate review of the environmental, economic and social impacts of GE soybean, corn and cotton use on U.S. farm sustainability [6].

Based on this review of the peer-reviewed evidence, the NRC consensus process arrived at four overarching findings and recommendations [6]:

1. <u>Finding</u>: The use of the GE soybean, corn and cotton varieties has improved some environmental conditions compared to the conventional cropping alternatives, in particular lower use of more toxic compounds and complementary reduced tillage that decreases soil erosion and polluted runoff. Some effects extend beyond the farm boundaries of adopters to the landscape level, such as suppression of undesirable pest populations with Bt Corn [16]. However, rapidly increasing weed resistance to glyphosate could erode both the farm and landscape environmental benefits of

glyphosate-resistant crops unless effective strategies are found to manage such resistance. It has been argued that this systemic resistance buildup problem to such pesticide technologies will constrain the long-term sustainability of GE crops [17]. Gene flow to wild or weedy relatives has not become a serious problem because compatible relatives of corn and soybean do not exist in the U.S. and are only local for cotton.

2. Recommendation: An inclusive group of public agencies, industry, universities, farmer groups, and non-governmental organizations should collaborate to document emerging weed-resistance problems and to develop cost-effective resistance-management programs and practices that preserve effective weed control in HR crops. Potential improvements in water quality due to GE crops require more monitoring and evaluation.
3. Finding: The use of GE soybean, corn and cotton crops has provided diverse economic benefits to adopting farmers that generally outweigh additional technology fees for these seeds and other associated costs. The substantial but not universal benefits can include reduced operating costs, higher yields, increased farmer safety, and/or greater flexibility in farm operations. The economic effects on producers of non-GE crops, such as adventitious gene flow to organic crops and decreased pesticide prices, are mixed and not well understood.
4. Recommendation: More public and private research resources should be devoted to assessing the economic effects of GE crops on adopting farmers, growers of non-GE crops, livestock producers, consumers, and others in the agricultural supply chain.
5. Finding: While the use of GE crops is a dynamic process that both affects and is affected by the social networks that farmers have with each other, with other actors in agriculture, and with the broader public, the social effects of GE-crop adoption have largely been overlooked. For example, although the proprietary terms under which industry has supplied GE seeds has not adversely affected the economic welfare of farmers using GE crops to date, ongoing research is needed to investigate how market structure may evolve and affect access to non-GE or single-trait seed and the effects of increasing market concentration of seed suppliers on yield benefits, crop genetic diversity, seed prices, and farmers' planting decisions and options.
6. Recommendation: More public and private research resources should be devoted to assessing the social effects of GE crops on adopting farmers, growers of non-GE crops, consumers, others in the agricultural supply chain, and rural communities.
7. Finding: Genetic engineering could be used in more crops, in novel ways beyond herbicide and insecticide resistance, and for a greater diversity of purposes. For example, with reforms in R&D processes, GE technology could help address food insecurity by reducing yield losses via its introduction into minor crops, with the development of other yield protection traits like drought tolerance, and could also address "public goods" issues such as carbon sequestration.
8. Recommendation: Universities, government and private research institutions should be eligible for government support to develop GE crops that can deliver valuable public goods. Intellectual property patented in the course of developing major crops should continue to be made available for such public goods purposes to the extent possible, such as for plants that reduce off-farm water pollution and improve nutritional quality that deliver health benefits to the broad public.

Given the lack of information on social dimensions and some missing economic and environmental performance data for GE soybean, corn and cotton varieties, the NRC report could not draw firm conclusions on the contribution to sustainability of the popular GE varieties on U.S. farms. The dearth of evidence on the social effects of GE crops contrasts sharply with the intense studies of the negative and positive social aspects of previous major agricultural technologies. We argue below that the neglected study of some contentious social issues surrounding GE crops, e.g., control of GE crop development by a few large companies and the effects of the adventitious presence of GE material in organic crops, will thwart efforts to explore the full potential of GE crop technologies in contributing to sustainable agriculture. Sections 4 and 5 explore some of the missing social dimensions and approaches to insert them into GE crop development. In this regard, recall that the concept of sustainability is necessarily holistic. It is not possible for a technology to contribute to sustainable development if it merely contributes to “economic sustainability” or “environmental sustainability,” for the short run, or for a small subset of farmers and agribusinesses.

This last observation raises a fundamental point about the process of searching for GE crop technologies that can be elements of a sustainable agricultural development trajectory. To make an argument that these technologies contribute to sustainability, it is necessary to address how these technologies contribute simultaneously to long-term economic, ecological and social sustainability in an equitable fashion. That is, all three dimensions need to be fully engaged in the discovery process from the outset in searching for such innovations. Using a mathematical analogy, the process should be one of solving a system of three simultaneous equations rather than trying to find the best GE crop for each goal (economic, environmental and social) individually, and then searching for ways to meld the technologies together afterwards. This type of simultaneous search and discovery process emphasizes that each dimension depends on the other *i.e.*, they are endogenous, a characteristic of holistic systems. Separate processes to achieve the three individual goals will generally lead to an inferior solution than pursuing them simultaneously. The individual approach also risks a path dependency limitation. For example, if the process starts with the search for a more economical HR crop that has not considered the full set of opportunities for environmental and social improvements, such a discovery process likely will constrain the full sustainability potential of the technology.

GE crop adoption in countries outside the U.S. has generally been uneven. This may be due in part to the fact that GE crops generally have not been developed to respond to the peculiar needs and conditions of many countries. One reflection of this mosaic growth pattern is that while 134 million hectares were planted worldwide to GE varieties in 2009, this only constitutes approximately 9 percent of the 1.5 billion hectares of global cropland in use that year. In other words, the GE crop revolution has been confined to a small subset of countries (25) and a small set of crops to date, generally the same three crops that have been adopted in the U.S. and are widely traded globally, *i.e.*, corn, soybeans and cotton. Thus, the U.S., Argentina, Brazil and Canada accounted for nearly 86 percent of all GE crop plantings in 2009, while India, China and other countries made up the remaining 14 percent of the total [14]. Only very small plantings of GE crops have occurred in African countries, and in particular, there seems to be slow development of GE crops that are important to African societies but are not widely grown in the North and are directed primarily at local, rather than global, markets. This does not exclude the possibility that GE crop strategies could be applied to crops that are popular food sources in developing countries. For example, research on rice and wheat could be applied to millet or tef to increase yields or diminish disease problems, and research on legumes could be applied to groundnuts or cowpea to address pest or disease issues [18]. However, these applications remain mostly hypothetical. For example, the Cassava Biotechnology Network, a multi-stakeholder group established in 1988, has been working to bring GE cassava varieties to African farmers [19]. However, field trials of GE cassava with enhanced beta carotene levels began only in 2009 and commercialization has yet to occur. There are some who hypothesize that the costs associated with regulatory compliance may be hindering GE applications to minor crops. Evidence for this hypothesis remains mostly anecdotal. However, such claims must consider that the larger bundle of development and regulatory costs associated with commercializing any GE minor crop may be too high to warrant private investment given the limited market revenue potential. For all but a few major crops, the opportunities for positive returns on private investment in GE crop development may be limited [6].

In places like Japan, Korea, and some European countries, an additional reason for the muted adoption of GE crops is public resistance. Virtually no commercial plantings of GE crops have occurred in European countries and Japan. In the Japan case, the Japanese government, through its support of research and trials, is trying to slowly advance the use of GE technology in agriculture, but concerns about the technology raised by consumers and other actors remains strong and a possible impediment, although imports of GE commodities into Japan is legal [20]. Research suggests that many Japanese consumers held very strong preferences against food products with GE ingredients around the turn of the century [21].

In the European Union, the ban to date on GE crop plantings reflects continuing interest group and consumer concerns about potential environmental and human health risks, the lack of institutional capacity to address those effects if they emerge, and potential negative impacts on the structure of agriculture [22]. Another factor may be the relative strength of agricultural chemical firms in Europe, who have been less aggressive than US agribusinesses in developing GE crop innovations. Graff, Hochman and Zilberman argue that the European agricultural chemical companies' abstention from efforts to implement a new regulatory regime for GE crops served to enhance the voice of oppositional interest groups in the European policy debates [23].

In Africa, some scholars argue that well intentioned but misinformed advocacy groups who oppose agricultural development involving GE crops and other non-indigenous technologies have thwarted progress [24]. The strong opinions against GE crops do not always match the consensus of scientific organizations. For example, major comprehensive reviews of GE crops have discovered no serious human or animal health risks, except in the case of allergies to unknown ingredients, e.g., peanut content [25]. Nonetheless, concerns are real expressions of angst about GE crops by environmental and other interest groups and many consumers. Although genuine environmental risks may exist for some GE crops in particular ecological contexts, e.g., gene flow to weedy relatives, we argue below that the origins of much of this opposition may ultimately be found in social concerns, including those about concentrations of economic power and the distributions of risks and benefits of GE crop technologies. In particular, consumer attitudes about food related technologies appear to be more influenced by their own perception of risk, rather than the technical analyses of risks provide by experts [26].

Organizations advocating for more GE crop plantings forecast a second generation of HR and IR crops that will increase yields and other desirable traits [14]. However, evidence is emerging that the development of GE crops may be reaching a plateau. Graff, Zilberman and Bennett document the decline in transgenic product quality innovations since the early 1990s [27]. Although the agricultural biotechnology industry often projects an image of developing new GE crop technologies that move beyond pest control strategies and for a wider range of crops, few such innovations have been commercialized. If such a pattern continues, it portends that few new varieties of GE crops will become available to promote agricultural sustainability. The reasons for this slowdown or stagnation have not been empirically confirmed, and are likely varied in nature. One key factor may well be the lack of public investment in GE crop R&D that is targeted at improvements that focus on public good spillover effects. As we will explain below, public and private R&D needs to be guided by an explicit set of sustainability criteria if GE crops are to fulfill their potential to foster sustainable agricultural systems.

4. Assessing the Sustainability of Current GE Crops

Efforts to assess the sustainability of GE crops have tended to focus on ecological or environmental dimensions, including ecological risks and benefits associated with GE crops [28]. Reduced chemical usage and the potential to avoid killing non-target, non-pest species are included as benefits. Invasiveness, indirect effects on non-pest species, and weed and pest resistance are examples of potential negative side effects [29,30]. Similarly, it is likely that GE crops have economic and social risks and benefits. Presumably, if an adequately complex, integrated systems approach were developed to consider simultaneously all of the potential risks and benefits, GE crops could be developed to fit into a sustainable development approach. However, GE development is often framed primarily as a technical issue, as opposed to one that includes socioeconomic and equity effects through which discussions might focus on public goods and concerns regarding the distribution of a range of risks and benefits associated with GE crops.

When scholars do incorporate social equity factors into evaluations of GE crops, they tend to treat the issue as a discrete dichotomy. For example, Lyson categorizes GE crops and sustainable agriculture as emerging from two distinct paradigms [4]. GE crops are consistent with a reductionistic conventional agricultural paradigm comprised primarily of experimental biology and neoclassical economics. In contrast, he contends, sustainable agriculture is grounded in a more holistic ecological and community development paradigm. Although Lyson’s argument is useful for clarifying the distinctions between sustainable and conventional agricultural paradigms, his portrayal of GE crops as inherently connected to the conventional one is not convincing [4]. It may be that the molecular biological techniques used to create GE crops are being employed primarily to maintain the conventional agricultural paradigm. However, we would argue there is nothing inherent to molecular biology R&D that prevents it from being deployed in a more holistic agricultural system. However, we accept that the current private and public institutions that influence the trajectory of GE crop technologies are unlikely to produce such sustainability innovations. To demonstrate this, we build on some seminal work on this topic to explain the current R&D trajectory and suggest reforms necessary to shift to that path.

Hubbell and Welsh have developed a useful conceptual approach for evaluating genetically engineered crops based on a continuum, rather than a discrete dichotomy [31]. Their approach is important in part because they include socioeconomic factors in their conceptual model. On the less sustainable end of their continuum is a set of cropping practices based upon heavy chemical usage in the production of extensive acreage of a few, genetically similar crops. On the more sustainable end is low-input, multi-crop, and integrated crop and livestock production systems. A farming system that uses comparatively fewer chemicals than conventional production systems and employs other ecologically friendly practices may not be characterized as fully sustainable, but may be characterized as moving along the continuum assuming it addresses salient social and economic issues.

- To illustrate their conceptualization, Hubbell and Welsh describe three scenarios in which GE crops may be characterized as enhancing the transition from less sustainable to more sustainable farming systems [31]. First, HR transgenic crops have reduced the use of agricultural chemicals most harmful (toxic) to human beings and the environment. In the second scenario, transgenic crops could be useful in helping farmers transition out of chemical-intensive agriculture by adopting crops engineered to produce biological pesticides, such as Bt crops, to replace the application of harmful chemicals. Although some evidence exists that Bt crops can promote integrated pest management, the crops still may not advance all of the environmental aspects of sustainability on the continuum, because gene flow and pest resistance build-up remain persistent challenges [32,33]. In the third scenario, Hubbell and Welsh consider the possibility that transgenic crops could be instrumental in promoting an integrated pattern of sustainable agricultural development [31]. "Potential benefits of these types of transgenic crops include reduced toxic chemical use, higher yields or improved output quality, reduced costs of production, reduced soil erosion, and increased farmer control and autonomy over the production process" ([31], p. 48).

To our knowledge, there are no transgenic crop developments that fit into the third category. GE crop proponents have promised improved nutrition in food, drought resistant varieties, and a host of other beneficial attributes. However, the promises have yet to be converted into much in the way of tangible outcomes. This may be because, as West (2007) observes, the R&D agenda has largely been driven by large agribusinesses [22]. However, even if some dramatic developments were to be forthcoming, the development of these new crops would also need to occur in a manner that addresses socio-economic equity issues before these GE crop developments could earn the label of sustainable.

Building on Ervin and Welsh, we propose the following criteria, which must be adopted in an integrated fashion, for GE crop development to help advance sustainable agriculture goals [8]:

1. Engineer traits that mimic ecological processes and natural defenses that confuse, avoid or deter pests or delay or tolerate damage and not rely on the killing of pests through engineering toxins into the plant or making the plant able to withstand the application of herbicides.
2. Transform the crop to minimize or eliminate transmission of engineered traits through pollen dispersal and other mechanisms.
3. Innovate GE crops that sustain the economic viability of adopting farmers by protecting/increasing yields, enhancing quality for food, fiber and energy purposes, reducing input costs, and/or increasing flexibility and safety for managers.
4. Develop GE crops in ways that farmers and other stakeholders can convey their preferences and knowledge about crop performance and its effects in the supply chain and beyond the farm boundaries.
5. Construct intellectual property (IP) arrangements such that farmers can save and replant—but not resell—the seeds to tailor the technologies to their local conditions. This approach would

shift the locus-of-control of seed production toward the farmer and likely increase crop biodiversity, but retain some protection for seed firms' investments.

6. Use public support mechanisms to stimulate the development of GE crops that deliver valuable public goods, such as reduced nutrient applications and runoff and renewable energy feedstocks, for which private firms have inadequate incentives to commercialize.
7. Create a differentiated risk assessment and management system that fast tracks GE crop innovations that adhere to these sustainability criteria to reduce regulatory cost burdens.

We further our argument of the importance of social, as well as economic and ecological, dimensions of sustainability by exploring four social dimensions that need to be addressed to enable GE crops to be utilized within a sustainable agricultural system: farm structure, consolidation and concentration in the agricultural system, institutional capacity for R&D, and citizen and consumer participation. As a first step, GE crops should be evaluated on a continuum according to these social structural categories to help determine their potential for contributing to more sustainable agricultural systems.

<u>*Farm Structure*</u>

Today, approximately 10% of U.S. farms account for 75% of agricultural commodities produced [34]. However, nearly 2 million smaller farms deliver the remaining 25% of commodity production, a significant contribution [35]. What may be even more important from the perspective of family and community wellbeing, those 2 million farms account for an important portion of many rural household livelihood strategies as well as contribute to community stability. Scholars are investigating whether farming as "a household livelihood strategy" will persist, as well as the benefit to rural areas of having a settled countryside ([36], pp. 103-104).

Structural issues in agriculture are important for understanding crop development processes. In a study of wheat growers in Washington State, Glenna *et al*. found that farmer interests in different wheat varieties can be explained by farmers' social characteristics [5]. Larger, wealthier farmers engaged in conventional agricultural production were more likely to express interest in Roundup Ready wheat, while smaller, less conventional farmers were more interested in wheat varieties with traits suitable for special markets and in perennial wheat varieties that would not need to be planted every year. The implication is that farmers' social and economic positions in the structure of agriculture influence the values they place on agricultural technology strategies. Thus, if the development and dissemination of GE technology is to have broad impact, options may need to be targeted to the needs of different farmers. The needs and concerns of a variety of farmers, including small holders in the U.S. and around the world, need to be incorporated into the GE technological development process if it is to have any hope of contributing to long-term agricultural, as well as rural, sustainability.

However, GE crop technology, as it has been developed to date, is one in a series of technologies implicated in the transition of an agricultural structure from numerous small farms to consolidated large farms, since capital-intensive farms tend to benefit disproportionately from technologies designed to reduce labor costs [37]. This is particularly true in industrialized countries where the transition to fewer, larger farmers was quite possibly exacerbated by the development of GE crops [38], although the NRC report found mixed results for this proposition.

There are concerns that GE crop technologies not only are targeted primarily towards larger farms to cover commercialization expenses, but may negatively affect smaller farms. When a new technology lowers production costs, including labor expenses, some of those who work in the industry must accept lower wages or transition out of the industry. Kloppenburg *et al.* claim this shift is part of the demise of a moral economy, in which the operative form of capitalism systematically consigns people and nature to being subservient to a predominantly private market construct [39]. By contrast, a moral economy would be responsive to the needs of the full spectrum of people and to the natural ecosystem.

These critical evaluations of GE crops and the structure of farming underscore that most current GE crops reduce labor requirements and other input costs and facilitate increases in farm size. However, GE crops need not *inherently* favor larger agricultural production systems. For example, as Mendum and Glenna have documented, a conscientious and socially reflexive university plant breeder can develop a breeding program that is responsive to small and medium-sized, and even organic, farmers [40]. Within such a program, they contend, GE techniques could hypothetically be utilized in such a way that they could benefit small and medium-sized farms. Such a plant breeding program needs to be constructed in a way that relies on public funding and public-interest intellectual property policies, given that private R&D likely will not see sufficient economic reward in serving small market segments.

One of the key tenants of sustainability is assuring the opportunity for contributions from all stakeholders in the system in question. Notwithstanding focus groups or grower meetings to test market demands for new products, the development of GE technology in the U.S. to date has not been associated with extensive input by farmers or other stakeholders. Farmers are generally thought of as adopters whose role is to purchase and use a technology developed off-farm, and citizens' role is conceptually confined to the consumption act. It is reasonable to hypothesize that the comparative lack of development of new GE varieties for minor crops, to address the full suite of ecological problems, and to enhance nutritional quality for those who eat these products, is due in part to limited stakeholder participation in the technological development process. A rare exception to this pattern is the development of a GE papaya resistant to papaya ring spot virus by government and university scientists working closely with Hawaiian growers and other stakeholders [41]. This GE crop innovation was initially made freely available to Hawaiian producers by developers to foster broad adoption necessary to control the disease. Subsequently, it was licensed from the patent holders and sold commercially. We believe that such participatory crop breeding programs, as well as those that are committed to open source breeding, offer opportunities to make the biotechnology development process more collaborative and thus more sustainable, than the current research structure.

Consolidation and Concentration in the Agricultural System

Several scholars, including Heffernan and McMichael, argue that large agribusinesses appear to have gained monopolistic or oligopolistic control of agricultural input and commodity markets, enabling them to extract greater than competitive profits at the expense of farmers and to exert greater political influence [42,43]. Hendrickson and Heffernan's work supports the contention that a small group of agribusinesses have achieved oligopolistic control of commodity value chains [44]. Concentration has increased since the late 1970s and early 1980s, when the enforcement of antitrust regulations was relaxed. Regulators operated on the assumption that it was possible to "balance the efficiency gains from concentration with the inefficiencies associated with possible anti-competitive behavior…." ([45], p. 553). Heffernan and Constance credit the weaker enforcement of antitrust regulations in the agrifood system with the rise of corporate consolidation [46].

GE seed development, in large part, has occurred within this political and economic context of concentration in the agrifood sector. As seeds became the mechanism for agricultural biotechnology firms to deliver their intellectual property to agricultural raw material producers, agribusinesses began a process of vertical and horizontal integration [38,46,47]. As a result of these efforts, two companies, DuPont-Pioneer and Monsanto, came to account for 56% of the U.S. seed corn market [48]. Globally, four companies account for 29% of the world market in commercial seeds [49]. Since Monsanto's seeds account for 90% of the world's genetically modified crop acreage, they likely have secured a near monopoly in those markets and can exercise significant control over seed access and prices [50].

Glenna and Cahoy have documented how intellectual property ownership came to be concentrated in a few large companies [51]. Analyzing patent ownership in the areas of GE corn and GE non-corn plants, they found that there are 37 discrete owners of the 525 GE corn patents and 118 discrete owners of the 1013 GE non-corn patents. However, due to mergers and joint ventures, the top three firms in the GE corn category control 85.0% of the patents, and the top 3 firms in the GE non-corn category control 69.6% of patents. These findings indicate that there is substantial concentration of ownership of the intellectual property associated with GE crops. That degree of concentration likely affects the portfolio of GE and non-GE cultivars available to all types of farmers. This level of concentration could potentially limit economic returns to farmers and limit the potential for farmers to affect decisions regarding future developments of GE technology.

We have argued that to promote a more sustainable agricultural system, it is necessary to address the needs of a variety of farm types, as well as to encourage input from users of the technology and consumers of the crops that are ultimately produced. Thus, it will be critical to have policies that promote more competitive markets that are also equitable, *i.e.*, do not unduly favor large agribusinesses over farmers and consumers. One key related policy consideration has to do with the purpose and effects of intellectual property (IP) policies that govern access to GE crop technologies.

Institutional Capacity for Public Goods R&D

The development of a robust national R&D program is premised on the presence of distinct public and private research institutions [52]. Private sector institutions, such as agribusinesses, tend to focus on major crop varieties and other crops, which are likely to be planted in volumes that will generate sufficient revenue to cover R&D, regulatory and manufacturing costs and earn a profit. In contrast, public sector institutions, such as universities, are expected to conduct research on crops that may be deemed valuable for society, even though their limited scale might not be profitable in a financial sense [53]. However, policies directed at promoting university-industry biotechnology research collaborations may be blurring this division of labor and undermining the viability of public sector agricultural research to conduct research on non-mainstream crops and problems.

Although it is difficult to identify the specific time that private science emerged as the dominant model in the overall U.S. R&D picture, 1980 stands out as a watershed year. In the immediate post-war decades, public investments in R&D went primarily to public research institutions. However, by 1980, the private sector, rather than the federal government, was the primary source of R&D funding [54]. Since then, through new institutional arrangements, financial investments and strategic public and private research partnerships, the private sector's influence on national R&D has grown.

In the agriculture sector, IP protections that accompany GE crops have inspired the private sector to invest in applied agricultural research. Although this can be seen as a good in general, it is important to recognize that private-sector GE crop investments have overwhelmingly been targeted at plants and traits that are of interest to the largest farms with the most widely planted crops [55]. The two dominant commercialized traits, HR and IR, were developed to realize a return on substantial R&D investments for agri-biotechnology firms as they sought to switch from a chemical pesticide approach to a life science regime [7]. These traits fit easily within the firms' established and, therefore, familiar approaches to pest management [18]. While this is logical from the standpoint of these private sector firms, certain public interests in GE innovations consequently remain unaddressed. Thus, the United Nations Food and Agriculture Organization has raised concerns that many fruit, vegetable and specialty crops will be neglected if the emphasis remains on private-interest science [55].

At least two studies lend evidence to support concerns that GE crop research is shifting university research toward a private-sector agenda. Analyzing applications for GE crop field trials, Welsh and Glenna found that university research on transgenic crops has increasingly mirrored the research profile of for-profit firms [56]. The implication is that over time fewer resources will be devoted by universities to GE technologies for minor and specialty crops that do not have the potential for turning a significant profit to agribusinesses. In a related national study of academic scientists conducting research related to agricultural biotechnology, Buccola *et al.* found that federal and state research support encourages more basic research, whereas industry and foundation support more applied research in U.S. universities, and that downstream (*i.e.*, more applied) research tends to be legally and economically more excludable than upstream (*i.e.*, more basic) research [57]. They conclude that publicly-funded research, in contrast to privately-supported research, offers the highest potential for achieving public goods, such as the basic science of genetic mechanisms, broadly-accessible platform technologies, and nonmarket environmental services [57].

Although concerns about stagnant funding and IP policies are important, strategies for addressing the concerns are quite straightforward. For example, the federal government could decide to provide robust formula funding to research universities to support public-interest research [58]. Likewise, institutional mechanisms can be put in place to prevent the exclusion or limiting of access to university research because of intellectual property held by the private sector or by other universities [59,60].

However, in recent years, land-grant-university plant breeding programs have been transformed in two ways that may be having a negative impact on the ability to conduct research that have positive public goods impacts. First, they have become less relevant in shaping national and global research agendas because the breeders in the private sector now outnumber public-sector breeders. Second, within university plant breeding programs, traditional plant breeding has largely been replaced by biotechnology programs. The hyperbole about the promise of GE crops by their advocates has led to the decline in funding for classical plant breeding and in numbers of classical plant breeders, and shifted research efforts from public toward private efforts [61,62].

A similar situation has emerged in U.S. land-grant-university weed sciences programs. A survey of weed scientists revealed that a plurality of weed scientists focused on herbicide efficacy and maintenance, and that these researchers were mostly funded by the private sector. A far smaller group of weed scientists received public sector funds to support a more complex systems approach, such as ecological weed management [63].

Finally, as we have noted previously, there is now a very limited amount of public sector funding, and virtually no private sector funding, to investigate the social impacts of GE biotechnology. Taken together, all these trends in research and development raise concerns about the institutional capacity to develop GE technologies that could contribute to the furthering of a sustainable agricultural system. In stark terms, the amalgam of public and private sector research systems is not oriented towards supporting research in GE technologies that reflect the wide variety of crops, agronomic problems, and social dimensions that will be needed if society is truly to achieve sustainable development [6]. Moreover, the comparable lack of R&D infrastructure in developing countries makes it highly unlikely that GE crop improvements will be applied to specific agronomic challenges in those countries. Developed nations and development NGOs would need to make massive investments in crops and problems of concern to stakeholders, perhaps via Consultative Group for International Agricultural Research (CGIAR) research stations and agricultural universities in developing nations, before the public research systems in developing nations would be capable of developing GE crop technologies in these nations that address local problems in a holistic manner.

Consumer and Citizen Acceptance and Participation

Although technologies may not harbor essential qualities that determine their social impacts, some paradoxes become more common as science and technology become more advanced. A sustainability approach requires inclusive stakeholder participation to determine the appropriate distribution of risks and benefits of any technology. This focus on solving the problems of intended users through collaborative stakeholder involvement is a fundamental tenet of sustainability science. Unfortunately, as science and technology have become more prominent in society, its practitioners have tended to rely upon the application of science in the form of social engineering and the control of nature and to de-emphasize the role of citizen participation and critical reflection [64,65]. This reluctance may be due in part to the belief in some quarters that experts would not benefit by consulting laypeople. It may also be due to the time-consuming and costly challenges involved in engaging with stakeholder groups.

It is not uncommon to find studies that portray consumers or citizens who express concerns about GE crops as being misinformed or self-indulgent to the point of hurting the development process [66]. This perspective is countered by philosopher Andrew Light, who stated that portraying people opposed to GE crops as needing a scientific education to rectify their ignorance reflects in itself an ignorance of fundamental differences between competing worldviews and people's rights to hold different worldviews. He further argued that GE is about more than just perceptions of scientific techniques. It is "about how people have felt excluded from making decisions…. If you don't like that, then fundamentally you don't like the democratic process" [67]. Since democratic participation is a central tenant of sustainability, it is worthwhile to consider how to invite consumer and citizen participation in determining acceptable risks and benefits of GE crop technologies, as well as in evaluating their social impacts.

Labeling foods with GE ingredients and providing unbiased information about GE technologies and their effects may be the most basic way that consumers can be empowered. Consumer advocates argue that consumers have a right to know what is in their food. For example, a 2002 national survey showed that 85% of Americans want a label on foods derived from GE crops although their responses did not consider the costs of implementing such a labeling system [68]. Others counter that labeling would add unnecessary expense to food production. An editorial in the journal *Nature* observed that many of the safety concerns of GE foods are exaggerated, but that there are legitimate risks that should be explored. More importantly, the editorial concludes, consumers lose trust in their food and the regulatory mechanisms when information is not forthcoming. Therefore, paradoxically, labeling may be a necessary step in regaining consumer trust in the food system, and thus in generating the improved understanding of the technology that proponents hope for [69].

Consumer and citizen perspectives, and national policies, tend to vary between nations. Europe and Japan, for example, tend to have stricter regulations and more citizen concerns than the U.S. and other countries regarding GE crops [22]. In 1994, as synthetic growth hormones were being considered for dairy production, the U.S. Executive Branch concluded a review of literature on the social consequences of rBST with this statement: "At no time in the past has the U.S. Federal Government prevented a technology from being adopted on the basis of socioeconomic consequences" [70]. Comparing Europe and the U.S., Kleinman and Kinchy describe variations in pervasive ideologies that define the boundaries of what is considered legitimate criteria in policy debates [71]. They highlight three ideologies in the U.S.: (1) technological developments are synonymous with progress, (2) scientific and technical decisions should be made independently of considerations of social values, and (3) a market-place of individuals in pursuit of private gain provides a more efficient means of determining the appropriateness of a technology than a government regulatory body. In Europe, by contrast, a historically-based social welfare discourse assumes that neither market nor private mechanisms alone can solve all social and economic problems. Therefore, it is appropriate for the state to intervene on the basis of social values to ensure social and economic benefits from science and technology. Kleinman and Kinchy also point to attributes about European Union policy making that help to explain the capacity of actors to elevate social impacts in the legal and regulatory process [71]. They note that the EU policy making process is fragmentary, susceptible to multiple veto points, and that the presence of multiple parties undermines the capacity for party discipline and deal making. They contrast this with the two-party system in the United States and the winner-take-all approach to policy making. However, even the European Union recently developed a policy of evaluating only the relatively depoliticized issues of health and safety of GE technologies rather than socioeconomic consequences [72].

Austria has taken a unique position to incorporate social and economic impacts into the regulatory process. Seifert and Torgersen explain that a 1992 Austrian commission established to consider GE products stated that social sustainability (Sozialverträglichkeit) should be considered in regulatory processes, that disclosure of risks and benefits should be mandatory, and public participation should be encouraged [73]. Paragraph 63 of the Austrian Genetic Engineering Act specifically stated that genetically engineered products must not lead to social unsustainability and would not be approved for use "if it may be assumed on a technical basis that such products would lead to an unbalanced burden on society or on social groups, and if this burden no longer appears acceptable to the population for economic, social or moral reasons" ([73], p. 303). That the Austrian model has not been adopted elsewhere adds further support to the proposition that people's perspectives on the link between technology and sustainability vary across nations. It further suggests that a nation's commitment to social sustainability must be very strong to offset the political and other costs of achieving such an agreement.

Thus, in some countries, public deliberation mechanisms have been developed to encourage citizen involvement in science and technology decision-making. The least radical of these mechanisms encourages scientists to acknowledge a social dimension to a problem and then promote dialogue to help all participants to recognize distinctions between the social and technical dimensions of a controversial technology. Near the other end of the spectrum, lay citizens challenge the rules of the scientific method, are involved in the production and evaluation of knowledge, and often assert that appropriate research methods must be shaped by non-technical considerations [74,75].

The mechanisms for democratizing science and science policy can include public hearings and forums, advisory committees, oversight panels and councils, public surveys, citizen juries, consensus conferences, participatory action research, science shops, and community based research [76]. As one might imagine, the effectiveness of these mechanisms for involving citizens in the process varies considerably [75]. Also, some have noted that such participatory democracy processes can destroy trust if the dynamics of the system are not well understood [77]. A key challenge in efforts to bring non-expert citizens into contact with experts and policy makers is to encourage participants to respect each other's positions. To address this challenge, scholars have pointed to the need to engage in deliberative democracy [76,78]. In a deliberative democratic process, people find their assumptions, knowledge and values evolving and changing from a self-focus to a community or public-good orientation [76,78].

We recognize that promoting public participation is not a panacea, is variable in terms of costs and benefits, and incurs several risks while offering potential benefits. One of the most obvious shortcomings is that narrow political and economic interest groups can distort public debates. For example, GE crop proponents and opponents alike may resort to misinformation tactics. As we noted above, in the case of Europe, agri-chemical corporations may have empowered GE crop opponents by failing to challenge the concerns raised by GE crop opponents because it suits the agri-chemical industry's commercial interests [23]. And some proponents of democratic participation in the implementation of science and technology acknowledge that only experts are qualified to address some questions and that powerful political and economic interests can capture a participatory process [79-81]. Indeed, such participatory processes require careful design and execution to minimize the risk of powerful groups on either side privatizing the public trust for their own purposes [13]. In the area of environmental management, which also must bridge expert and lay knowledge gaps, a National Research Council study that focused on environmental management concluded that, if done properly, public participation can improve the quality, legitimacy, and capacity of environmental management [82].

If cases emerge where narrow political and economic interests subvert a genuine democratic dialogue on the appropriateness of a new technology for a sustainable agriculture system, as Aerni [13] has observed, then the challenge becomes one of highlighting the corrupting interests with the goal of achieving a balanced public-interest public forum. However, we present this brief discussion on efforts to promote stakeholder participation to demonstrate that it is not just appropriate from the perspective of democratic ethics, but also feasible. The Cassava Biotechnology Network provides one model of engaging farmers, NGOs, companies and research institutes in the search for more sustainable cassava production systems [19]. To rise to the level of sustainability, GE crops can and should be evaluated through a range of democratic participatory processes. The processes should enable effective participation by each stakeholder group to find a joint and viable solution expeditiously rather than foster stalemate. Such involvement can help encourage the development of biotechnology to meet the full range of stakeholder needs, as well as lead to improved understanding of technological processes, and the risks associated with them, by the citizenry.

5. Conclusions and Policy Options to Innovate GE Crops for Sustainable Agriculture

The preceding analysis suggests that GE crop technology development needs to be more holistic and cognizant of social, as well as economic and ecological, aspects of the innovation and diffusion process if it is to make a major contribution to the fostering of more sustainable agricultural systems. Two strategies that would help achieve this goal would be to restore the centrality of the public sector in agricultural R&D and to open the technology development process to more democratic participation. We conclude with some policy options for moving the entities and actors involved in GE crop development and implementation in those directions. The discussion covers all three legs of the sustainable development stool—economic, environmental and social.

Sustain Economic Viability

Consider first the dual goals of satisfying human food, feed, fiber and biofuel needs while sustaining the economic viability of agriculture [9]. These provisioning and economic goals reside largely in the province of the private sector because the goods are sold in markets and farmers' economic viability depends primarily on market conditions. Economists often see the achievement of those goals as seeking dynamic efficiency in the markets for resources devoted to GE crop production, *i.e.*, maximizing the net present value of GE crops. However, achieving a dynamically efficient provisioning of goods and services, even fully accounting for externalities, does not necessarily satisfy the objective of sustainable development [83,84]. Dynamically efficient solutions generally result in more consumption of resources and goods by the current generation because the presence of a positive discount rate diminishes the value of resources and goods used by future generations.

Pursuing a sustainable development strategy effectively changes this relative preference for current consumption and resource use compared to the needs of future generations. The overarching goal of sustainable development from an economic perspective is to achieve non-declining (and possibly increasing) human welfare over time while addressing salient intragenerational equity issues. That goal is linked to building and maintaining four stocks of capital—manmade, natural, human, and social/institutional—such that future generations can achieve standards of welfare at least as great as the current generation [83]. To reach this sustainable path requires a shift from market-driven "efficiency prices" to "sustainability prices" that place greater relative value on future generations' use of resources while incorporating the negative and positive externality effects [84]. An example of a policy to move toward sustainability prices is the imposition of a tax on current consumption to encourage more saving and investment for future periods.

GE crops that satisfy the criteria to foster sustainable agriculture systems will confer both private goods, such as food, and public goods, such as environmental benefits (e.g., carbon sequestration). As such, policies designed to foster GE crop developments must address both types of goods. For private goods, economic theory contends that the effective provision of private goods will be fostered by "well functioning" markets that satisfy five requirements: (1) good quality information systems exist for buyers, sellers and investors; (2) significant barriers (private or public) to entry of new firms do not exist; (3) no single firm or small set of firms has enough power to influence prices; (4) distortionary public subsidies or other policies must not be in place; and (5) significant negative or positive externalities must not accompany the production of the goods.

A key role then for the policy process to sustain economic viability is to maintain well-functioning markets. For GE crops in particular, two policy areas deserve special consideration. The first is vigorous antitrust policies to deter excessive industry concentration that impedes the entry of new firms, can stymie innovation, and eventually cause higher prices for GE varieties. The biotechnology and seed industries have undergone extensive consolidation of firms during the past 15 years. Research has found that increasing concentration of the seed industry decreases research effort and innovation [85]. And as reported earlier, research indicates that concentration of ownership of the intellectual property associated with GE crops could well affect the portfolio of future GE and non-GE cultivars and limit economic returns to farmers [51]. It is difficult to imagine how benefits could be diffused across the full spectrum of farmers in such a context.

A second policy initiative to maintain economic viability in agriculture is to reform public subsidies that cause over-production of certain crops, depress their prices and do not deliver other public goods. The United States, the European Union and other countries have a long history of providing public support to growers of certain crops for the express purpose of enhancing farm income and protecting small and medium-sized "family farmers". Counter to that intention, the subsidies often have been captured predominantly by larger farmers and capitalized into farmland values. This effect hinders new farmer entries and encourages the substitution of non-land inputs, such as fertilizers and pesticides for land. A little recognized effect of these crop subsidies is to distort private and public R&D expenditures toward the few subsidized major crops, such as corn, cotton and wheat, to the neglect of minor crop innovations, and to create incentives for R&D on non-land inputs. Thus, it is not surprising that the first generation of GE crops has focused mostly on pest control in major crops. This subsidized trajectory for GE crops is not aligned with the long-term economic viability tenet of sustainable agriculture. Thus, removing the government subsidies exclusively directed at major crops in the U.S. could stimulate the commercial potential for minor crops.

Enhance Environmental and Natural Resource Quality

Sustainable agriculture has the enhancement of natural resource and environmental quality as a core value. While some natural resource and environmental processes are mostly confined to the farm, such as soil quality, many impacts extend beyond the farm's boundaries. The incorporation of these "externalities", negative and positive, into farmer decision-making is also one of the requirements for well functioning crop markets as noted above. However, markets usually are unable to accomplish this internalization, because the benefits of such actions are often wholly or partially nonexcludable for other parties. As a result, farmers are precluded from collecting revenues from their environmental management actions. Many of the benefits are nonrival as well, thus precipitating classic public goods allocation problems among users. Improved downstream water quality, habitat for migratory wildlife, and reduced carbon emissions are typical examples.

A variety of policy approaches can be used to address public environmental goods situations in agriculture [86]. The central objective is to move to full environmental costing and ecosystem service payment schemes for agricultural systems. Traditionally, developed countries have emphasized financial and technical assistance to encourage farmers to voluntarily improve environmental conditions, but with little targeting to maximize cost effectiveness [87]. The main reason for this approach stems from the political power of farm groups to avoid or minimize the regulatory approach used in most other industries [86]. The nonpoint nature of many agriculturally related environmental processes makes the identification, monitoring and enforcement of regulations technically or economically infeasible in many situations. Given the heterogeneity in farming and environmental conditions, researchers have argued for flexible incentives to achieve performance standards wherever feasible to avoid cost-ineffective results [86].

Either positive incentives or negative sanctions can be used to incorporate agriculture's environmental externalities and public goods effects into farmers' cropping management decisions. For example, farmers planting GE crops that cause the adventitious presence of GE material in crops destined for markets that do not allow such material could be regulated through the planting of buffer strips of non-GE crops around their fields. Imposing such production restrictions and economic costs to reduce this negative externality would send a powerful signal to both the public and private R&D sectors to innovate GE crops to minimize or eliminate transmission of engineered traits through pollen dispersal and other mechanisms (as expressed in condition 2 above). To reduce the regulatory impact on farmers, government agencies can create a differentiated risk assessment and management system that only imposes such restrictions on GE crop applications with serious risks of such adventitious presence problems [88].

Although the negative environmental externalities of agriculture often receive most attention, the public and policy makers increasingly recognize that farming also conveys significant public environmental benefits to varied parties beyond farm boundaries [87]. Classic examples include terrestrial and aquatic habitat for migratory wildlife species and an appealing diverse countryside. A more contemporary example is carbon sequestration to reduce greenhouse gas concentrations from cropping systems that require low or no tillage. The public benefits emanate from the stocks and quality of natural capital managed by farmers, and therefore constitute a sustainability issue. Payments for such ecosystem services (termed PES) to farmers consistent with sustainability prices informed by participatory social processes can be provided at local, regional and national scales through various mechanisms [89]. Such PES schemes can incent both the private and public sector R&D systems to supply GE crop innovations that will supply public environmental goods. Implementing the fourth recommendation of the NRC report on GE crops would provide critical public support to universities, government and other research institutions to innovate GE crops that enhance valuable public environmental goods [6].

Enhance Social Sustainability (Relationships and Equity)

Perhaps the most efficacious mechanism for promoting social aspects of sustainability would be to promote citizen (including farmers, consumers and interest groups) participation at various stages of the R&D process in an engaged and open manner. Stakeholder participation can serve to empower lay citizens and scientists, since both may come to understand the knowledge and values of the others through the participatory process. Citizens are more likely to trust scientists and to promote expanding research funding for projects if they perceive such research as relevant. Furthermore, the research may be more attuned to nuance and variation in context if it combines the knowledge of the scientists with the knowledge of citizens. And citizens are more likely to accept the conclusions and become more likely to adopt subsequent technologies or policy proscriptions if they are involved in setting research agendas and determining the appropriate applications of science [75]. Similar to our use of a continuum to evaluate the sustainability of GE crops, Kleinman uses a continuum to evaluate the level of democratic participation in science [90]. On the one end of the continuum, scientists maintain self-governance, but seek input from citizens. Moving towards the more participatory end of the continuum, Kleinman offers examples of citizens actually becoming involved in conducting the scientific research [90].

There are many examples of national-level efforts to incorporate public participation into the scientific research agenda on agricultural biotechnology. The National Agricultural Biotechnology Council is a public forum that brings together diverse participants from private corporations, government agencies, universities, non-profit organizations, and other stakeholders to discuss and clarify concerns surrounding GE crops. One shortcoming in this approach is that participants have no assigned role in deciding research agendas. Science advisory committees also can enable greater participant influence, since they are charged with developing and coordinating the implementation of federal guidelines. However, despite the popularity of advisory committees, scientists largely define the public research agenda. Consensus panels go a step further by striving to make lay people central to deliberations and to permit non-experts to control the agenda [75]. Despite their name, these panels do not always arrive at consensus positions, a reminder of the need for effective design and execution in such processes. Research in the Philippines, Mexico and South Africa has shown that national academia are the most trusted stakeholders in addressing contentious GE crop issues, and therefore could play a facilitative role in achieving such consensus research outcomes [91].

As our review of trends in university research indicates, efforts to incorporate democratic participation into the research agenda may also start at a more modest scale than creating a national-level policy forum. Participatory plant breeding and surveys of farmers to determine their perspectives on wheat breeding programs are just two approaches in which scientists can incorporate farmers into the process of setting the research agenda and in shaping dissemination [5,40]. In at least one case, a participatory plant breeding project came close to achieving Kleinman's participatory ideal of involving laypeople in the process of generating science and technology [90]. Specifically, Washington State wheat breeders began developing participatory breeding pilot projects with farmers in 2003 to help farmers develop their own new wheat varieties which might be more suitable for their diverse farming systems and microclimates [92]. Within such a collaborative context directed at producing public goods and establishing long-term relationships, resistance to the introduction of GE techniques to improve crops might be less likely to emerge.

It is also important to provide opportunities for agribusinesses, including large, medium and small biotechnology companies, to participate in this GE crop development process. While these firms have the economic, political, and legal resources to promote their private interests, it is necessary to structure the participatory process to ensure that their voices do not dominate the public goods GE crop development agenda. In addition, although agribusiness possesses substantial R&D capacity and intellectual capital, public research plays an essential complementary role in providing basic and public science. A study of industry partners in university-industry agricultural biotechnology research collaborations found that agribusiness representatives believed strongly in maintaining the distinctions between public and private research organizations and in enhancing the R&D capacity of and resources for university scientists [93]. Although agribusinesses may not have the structural incentives to develop public goods *per se*, they have an incentive to work with the public sector to advance GE crop development to the extent they expect positive spillovers from such collaborations. For example, their participation in sharing intellectual property from major GE crops for minor crops in developing countries may result in improved goodwill in those countries. They may also gain insights into farmers' and consumers' preferences for GE crop attributes through their participation.

The kinds of social structural, policy, and institutional changes needed to make GE crops compatible with sustainable agriculture are immense. Such changes are unlikely to occur in the current climate of political divisiveness, scare tactics by all sides, and limited budgets without substantial citizen support, even mobilization efforts. However, failure to engage in a GE crop development process that integrates all major dimensions of the sustainability concept will in our estimation likely lead to a failure to achieve the promise of GE technology for contributing to meaningful sustainable development.

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References

1. Brand, S. *Whole Earth Discipline: Why Dense Cities, Nuclear Power, Transgenic Crops, Restored Wildlands, and Geoengineering are Necessary*; Penguin Books: New York, NY, USA, 2010.
2. Brookes, G.; Barfoot, P. *GM Crops: Global Socio-Economic and Environmental Impacts 1996–2006*; PG Economics Ltd: Dorchester, UK, 2008.
3. Ronald, P.; Adamchak, R. *Tomorrow's Table: Organic Farming, Genetics, and the Future of Food*; Oxford University Press: New York, NY, USA, 2008.
4. Lyson, T.A. Advanced agricultural biotechnologies and sustainable agriculture. *Trends Biotechnol.* **2002**, *20*, 193-196.
5. Glenna, L.L.; Jussaume, R.A., Jr.; Dawson, J.C. How farmers matter in shaping agricultural technologies: Social and structural characteristics of wheat growers and wheat varieties. *Agric. Hum. Values* **2011**, *28*, 213-224.
6. National Research Council. *Impacts of Genetically-Engineered Crops on Farm Sustainability in the United States*; The National Academies Press: Washington, DC, USA, 2010.
7. Ervin, D.; Glenna, L.; Jussaume, R. Are biotechnology and sustainable agriculture compatible? *Renewable Agric. Food Syst.* **2010**, *26*, 143-157.
8. Ervin, D.; Welsh, R. Genetically engineered crops and U.S. agricultural sustainability. *Choices* **2010**, *25*, 1-10.
9. National Research Council. *Toward Sustainable Agricultural Systems in the 21st Century*; The National Academies Press: Washington, DC, USA, 2010.

10. Gold, M.V. *Sustainable Agriculture: Information Access Tools*; U.S. Department of Agriculture, Alternative Farming Systems Information Center: Washington, DC, USA, 2009. Available online: http://www.nal.usda.gov (accessed on 4 March 2011).
11. Harwood, R. A history of sustainable agriculture. In *Sustainable Agricultural Systems. Soil and Water Conservation Society*; Edwards, C.A., Lal, R., Madden, P., Miller, R.H., House, G., Eds.; Soil and Water Conservation Society: Ankeny, IA, USA, 1990; pp. 3-19.
12. U.N. Food and Agriculture Organization (UN FAO). *Sustainability Issues in Agricultural and Rural Development Policies*; Trainer's Manual Volume 1; Food & Agriculture Organization of the United Nations: Rome, Italy, 1995.
13. Aerni, P. What is sustainable agriculture? Empirical evidence of diverging views in Switzerland and New Zealand. *Ecol. Econ*. **2009**, *68*, 1872-1882.
14. ISAAA. Global Status of Commercialized Biotech/GM Crops; The first fourteen years, 1996 to 2009. ISAAA Brief 41-2009: Executive Summary. Available online: http://www.isaaa.org/resources/publications/briefs/41/executivesummary/default.asp (accessed on 14 January 2011).
15. Benbrook, C. *Impacts of Genetically Engineered Crops on Pesticide Use: The First Thirteen Years*; Critical Issue Report; The Organic Center: Boulder, CO, USA, November 2009. Available online: http://www.organic-center.org (accessed on 21 March 2011).
16. Hutchison, W.D.; Burkness, E.C.; Mitchell, P.D.; Moon, R.D.; Leslie, T.W.; Fleischer, S.J.; Abrahamson, M.; Hamilton, K.L.; Steffey, K.L.; Gray, M.E.; *et al*. Areawide Suppression of European corn borer with Bt Maize reaps savings to Non-Bt Maize growers. *Science* **2010**, *330*, 222-225.
17. Welsh, R.; Hubbell, B.; Ervin, D.; Jahn, M. GM crops and the pesticide paradigm. *Nat. Biotechnol.* **2002**, *20*, 548-549.
18. Naylor, R.L.; Falcon, W.P.; Goodman, R.M.; Jahn, M.M.; Sengooba, T.; Tefera, H.; Nelson, R.J. Biotechnology in the developing world: A case for increased investments in orphan crops. *Food Policy* **2004**, *29*, 15-44.
19. Aerni, P. Mobilizing science and technology for development: The case of the Cassava Biotechnology Network (CBN). *AgBioForum* **2006**, *9*, 1-14.
20. Yamaguchi, T.; Suda, F. Changing social order and the quest for justification: GMO controversies in Japan. *Sci. Technol. Hum. Values* **2010**, *35*, 382-407.
21. Toyama, M.; Heffernan, J.W.; Hillers, V.N.; Jussaume, R.A., Jr.; Schultz, J.A. Consumers' Concerns and Behaviors Related to Biotechnology: Comparison between American and Japanese Consumers; Poster presentation at the *IFT Annual Meetings*, New Orleans, LA, USA, June 2001.
22. West, D.M. *Biotechnology Policy across National Boundaries: The Science-Industrial Complex*; Palgrave MacMillan: New York, NY, USA, 2007.
23. Graff, G.D.; Hochman. G.; Zilberman, D. The political economy of agricultural biotechnology policies. *AgBioForum* **2009**, *12*, 34-46.
24. Paarlberg, R. *Starved for Science: How Biotechnology Is Being Kept Out of Africa*; Harvard University Press: Cambridge, MA, USA, 2008.
25. National Research Council. *Safety of Genetically Engineered Foods: Approaches to Assessing Unintended Health Effects*; National Academies Press: Washington, DC, USA, 2004.

26. Rollin, F.; Kennedy, J.; Wills, J. Consumers and new food technologies. *Trends Food Sci. Technol.* **2011**, *22*, 99-111.
27. Graff, G.D.; Zilberman, D.; Bennett, A.B. Correspondence: The contraction of Agbiotech product quality innovation. *Nat. Biotechnol.* **2009**, *27*, 702-704.
28. Wolfenbarger, L.L.; Phifer, P.R. The ecological risks and benefits of genetically engineered plants. *Science* **2000**, *290*, 2088-2093.
29. Sisterson, M.S.; Carriere, Y.; Dennehy, T.J.; Tabashnik, B.E. Evolution of resistance to transgenic crops: Interaction between insect movement and field distribution. *J. Econ. Entomol.* **2005**, *98*, 1751-1762.
30. Sisterson, M.S.; Carriere, Y.; Dennehy, T.J.; Tabashnik, B.E. Nontarget effects of transgenic insecticidal crops: Implications of source-sink population dynamics. *Environ. Entomol.* **2007**, *36*, 121-127.
31. Hubbell, B.; Welsh, R. Transgenic crops: Engineering a more sustainable agriculture? *Agric. Hum. Values* **1998**, *15*, 43-56.
32. Carrière, Y.; Sisterson, M.S.; Tabashnik, B.A. Resistance management for the sustainable use of Bacillus thuringiensis in integrated pest management. In *Insect Pest Management: Field and Protected Crops*; Horowitz, A.R., Ishaaya, I., Eds.; Springer Verlag: Berlin, Germany, 2004; pp. 65-95.
33. Frisvold, G.B; Reeves, J.M. Resistance management and sustainable use of agricultural biotechnology. *AgBioForum* **2011**, *14*, in press.
34. Hoppe, R.A.; Korb, P.; O'Donoghue, E.J.; Banker, D.E. *Structure and Finances of U.S. Farms: Family Farm Report*; USDA Economic Research Service: Washington, DC, USA, 2007.
35. Lobao, L.; Meyer, K. The great agricultural transition: Crisis, change and social consequences of twentieth century US farming. *Annu. Rev. Soc.* **2001**, *27*,103-124.
36. Gertler, M.E. In *Resource Management in Challenged Environments*; Hardy, R.W.F, Segelken, J.B., Voronmaa, M., Eds.; National Agricultural Biotechnology Council: Ithaca, NY, USA, 1998; pp. 137-145.
37. Kloppenburg, J.R., Jr. *First the Seed: The Political Economy of Plant Biotechnology: 1942 to 2000*; University of Wisconsin Press: Madison, WI, USA, 2004.
38. Thompson, P.B. *Food Biotechnology in Ethical Perspective*; Springer: Dordrecht, The Netherlands, 2007.
39. Kloppenburg, J.J.; Henrickson, J.; Stevenson, S. Coming in to the foodshed. *Agric. Hum. Values* **1996**, *13*, 33-42.
40. Mendum, R.; Glenna, L.L. Socioeconomic obstacles to establishing a participatory plant breeding program for organic growers in the United States. *Sustainability* **2010**, *2*, 73-91.
41. Gonsalves, D.; Gonsalves, C., Ferreira, S.; Pitz, K.; Fitch, M.; Manshardt, R.; Slightom, J. Transgenic virus resistant papaya: From hope to reality for controlling payaya ringspot virus in Hawaii. APSNet, 2004, 1-12. Available online: http://www.apsnet.org/online/feature (accessed on 21 March 2011).
42. Heffernan, W.D. Concentration of ownership and control in agriculture. In *Hungry for Profit: The Agribusiness Threat to Farmers, Food, and the Environment*; Magdoff, F., Foster, J.B., Buttel, F.H., Eds.; Monthly Review Press: New York, NY, USA, 2000; pp. 61-76.

43. McMichael, P. *Development and Change: A Global Perspective*, 3rd ed.; Pine Forge Press: Thousand Oaks, CA, USA, 2008.
44. Hendrickson, M.; Heffernan, W. *Consolidation in the Food and Agriculture System*; Report to the National Farmers Union; Department of Rural Sociology, University of Missouri: Columbia, MO, USA, 5 February 1999.
45. Rubinfeld, D.L. Antitrust policy. In *International Encyclopedia of the Social and Behavioral Sciences*; Smelser, N.J., Baltes, P.B., Eds.; Elsevier Science Ltd: Oxford, UK, 2001; pp. 553-560.
46. Heffernan, W.H.; Constance, D.H. Transnational corporations and the globalization of the food system. In *From Columbus to ConAgra: The Globalization of Agriculture and Food*; Bonanno, A., Busch, L., Friedland, W.H., Gouveia, L., Mingione, E., Eds.; University of Kansas Press: Lawrence, KS, USA, 1994; pp. 29-51.
47. Boyd, W. Wonderful potencies? Deep structure and the problem of monopoly in agricultural biotechnology. In *Engineering Trouble: Biotechnology and Its Discontents*; Schurman, R.A., Doyle, D., Kelso, T., Eds; University of California Press: Berkeley, CA, USA, 2003; pp. 24-62.
48. Fernandez-Cornejo, J. *Adoption of Genetically Engineered Crops in the U.S*; USDA Economic Research Service: Washington, DC., USA, 2009. Available online: http://www.ers.usda.gov (accessed on 21 March 2011).
49. United Nations Conference on Trade and Development. *Tracking the Trend towards Market Concentration: The Case of the Agricultural Input Industry*; United Nations: New York, NY, USA, 2006. Available online: http://www.unctad.org (accessed on 4 March 2011).
50. Davoudi, S. *Monsanto Strengthens its Grip on GM Market: Group Maintains Lead as Billionth Acre Goes Under Cultivation*. Financial Times, November 16, p. 29.
51. Glenna, L.L.; Cahoy, D.R. Agribusiness concentration, intellectual property, and the prospects for rural economic benefits from the emerging biofuel economy. *South. Rural Sociol.* **2009** *24*, 111-129.
52. Dasgupta, P.; David, P.A. Toward a new economics of science. *Res. Policy* **1994**, *23*, 487-521.
53. Lacy, W.B. Generation and commercialization of knowledge: Trends, implications, and models for public and private agricultural research and education. In *Knowledge Generation and Technical Change: Institutional Innovation in Agriculture*; Wolf, S., Zilberman, D., Eds; Kluwer Academic Publishers: Boston, MA, USA, 2001; pp. 27-54
54. Gabel, M.; Geography, history impacts, and governance of multinational corporations. Paper presented at the American Association for the Advancement of Sciences. Global Inc: Denver, CO, USA, 2003.
55. United Nations Food and Agriculture Organization. *The State of Food and Agriculture. Agricultural Biotechnology: Meeting the Needs of the Poor?* UNFAO: Rome, Italy, 2004.
56. Welsh, R.; Glenna, L. Considering the role of the university in conducting research on agri-biotechnologies. *Soc. Stud. Sci.* **2006**, *36*, 929-942.
57. Buccola, S.; Ervin, D.; Yang, H. Research choice and finance in university bioscience. *South. Econ. J.* **2009**, *75*, 1238-1255.
58. Huffman, W.E.; Norton, G.; Traxler, G.; Frisvold, G.; Foltz, J. Winners and losers: Formula *versus* competitive funding of agricultural research. *Choices* **2006**, *21*, 269-274.
59. Atkinson, R.C.; Beachy, R.N.; Conway, G.; Cordova, F.R.; Fox, M.A.; Holbrook, K.A.;

Klessig, D.F.; McCormick, R.L.; McPherson, P.M.; Rawlings, H.R., III; *et al*. Public sector collaboration for agricultural IP management. *Science* **2003**, *301*, 174-175.

60. Graff, G.; Zilberman, D. An intellectual property clearinghouse for agricultural biotechnology. *Nat. Biotechnol.* **2001**, *19*, 1179-1180.
61. Knight, J. A dying breed. *Nature* **2003**, *421*, 568-579.
62. Traxler, G.; Acquaye, A.K.A.; Frey, K.; Thro, A.M. Public Sector Plant Breeding Resources in the US: Study Results for the year 2001. Available online: http://www.csrees.usda.gov/nea/plants/part/pbgg_part_study.html (accessed on 4 March 2011).
63. Davis, A.S.; Hall, J.C.; Jasieniuk, M.; Locke, M.A.; Luschei, E.C.; Mortensen, D.A.; Riechers, D.E.; Smith, R.G.; Sterling, T.M.; Westwood, J.H. Weed science research and funding: A call to action. *Weed Sci.* **2009**, *57*, 442-448.
64. Merelman, R.M. Technological cultures and liberal democracy in the United States. *Sci. Technol. Hum. Values* **2000**, *25*, 167-194.
65. Busch, L. *The Eclipse of Morality: Science*, *State*, *and Market*; Aldine De Gruyter: New York, NY, USA, 2000.
66. Hoban, T.J., IV. Public Concerns about biotechnology. In *Biotechnology and Sustainable Development: Voices of the South and North*; Serageldin, I., Persley, G.J., Eds.; CABI Publishing: Cambridge, MA, USA, 2003; pp. 279-280.
67. Lau, E. Grocery Quandary: For U.S. shoppers, a lack of labels limits choice on biotech products. *The Sacramento Bee*, 10 June 2004. Available online: http://www.sacbee.com/static/live/news/projects/biotech/c5_4.html (accessed on 14 June 2011).
68. Teisl, M., Garner, L.; Roe, B.; Vayda, M. Labeling genetically modified foods: How do US consumers want to see it done? *AgBioForum* **2003**, *6*, 48-54.
69. Editorial. GM foods debate needs a recipe for restoring trust. *Nature* **1999**, *398*, 639.
70. Lacy, W.B.; Glenna, L.; Biscotti, D.; Welsh, R. Agricultural biotechnology, socioeconomic effects, and the fourth criterion. In *Wiley Encyclopedia of Industrial Biotechnology*; Seidel, A., Ed.; John Wiley: New York, NY, USA, 2009.
71. Kleinman, D.; Kinchy, A. Why ban bovine growth hormone? Science, social welfare, and the divergent biotech policy landscapes in Europe and the United States. *Sci. Cult.* **2003**, *12*, 375-414.
72. Kinchy, A.; Kleinman, D.; Autry, R. Against free markets, against science? Regulating the socioeconomic effects of biotechnology. *Rural Sociol.* **2008**, *73*, 147-179.
73. Seifert, F.; Torgersen, H. How to keep out what we don't want: an assessment of 'Sozialverträglichkeit' under the Austrian Genetic Engineering Act. *Public Understanding Sci.* **1997**, *6*, 301-327.
74. Lacy, W.B. Empowering communities through public work, science, and local food systems: Revisiting democracy and globalization. *Rural Sociol.* **2000**, *65*, 3-26.
75. Lacy, W.B.; Glenna, L. Democratizing science in an era of expert and private knowledge. *Int. J. Technol. Knowl. Soc.* **2005/2006**, *1*, 37-46.
76. Hamlett, P.W. Technology theory and deliberative democracy. *Sci. Technol. Hum. Values* **2003**, *28*, 112-140.
77. Slovic, P. Perceived risk, trust and democracy. *Risk Anal.* **1993.** *13*, 675-682.

78. Rowe, G.; Frewer, L.J. Public participation methods: A framework for evaluation. *Sci. Technol. Hum. Values* **2000**, *25*, 3-29.
79. Fischer, F. *Citizens, Experts, and the Environment: The Politics of Local Knowledge*; Duke University Press: Durham, NC, USA, 2000.
80. Dryzek, J.S. *The Politics of the Earth: Environmental Discourses*, 2nd ed.; Oxford University Press: Oxford, UK, 2005.
81. Jasanoff, S. The Dilemma of Environmental Democracy. *Issues Sci. Technol.* **1996**, *13*, 63-70.
82. Dietz, T.; Sterns, P.C. *Public Participation in Environmental Assessment and Decision Making*; The National Academies: Washington, DC, USA, 2008.
83. Pearce, D.; Barbier, E. *Blueprint for a Sustainable Economy*; Earthscan Press: London, UK, 2000.
84. Pezzy J.; Toman, M. Sustainability and its Economic Interpretations. In *Scarcity and Growth Revisited: Natural Resources and the Environment in the New Millennium*; Simpson, R., Toman, M., Ayers, R., Eds.; Resources for the Future: Washington, DC, USA, 2005.
85. Schimmelpfennig, D.; Pray, C.E.; Brennan, M.F. The impact of seed industry concentration on innovation: a study of US biotech market leaders. *Agric. Econ.* **2004**, *30*, 157-167.
86. Batie, S.; Ervin, D. Flexible incentives for environmental management in agriculture: A typology. In *Flexible Incentives for the Adoption of Environmental Technologies in Agriculture*; Casey, F., Swinton, S., Schmitz, A., Zilberman, D., Eds.; Kluwer: New York, NY, USA, 1999; pp. 55-78.
87. Claassen, R.L.; Hansen, M.P.; Breneman, V.; Weinberg, M.; Cattaneo, A.; Feather, P.; Gadsby, D.; Hellerstein, D.; Hopkins, J.; Johnston, P.; *et al*. *Agri-Environmental Policy at the Crossroads: Guideposts on a Changing Landscape*; Agricultural Economic Report 794; U.S. Department of Agriculture, Economic Research Service: Washington, DC, USA, 2001.
88. Ervin, D.; Welsh, R. Environmental effects of genetically modified crops: differentiated risk assessment and management. In *Regulating Agricultural Biotechnology: Economics and Policy*; Just, R.E., Alston, J.M., Zilberman, D., Eds.; Spring Publishers: New York, NY, USA, 2006.
89. Farley, J.; Costanza, R. Payments for ecosystem services: From the local to the global. *Ecol. Econ.* **2010**, *69*, 2060-2068.
90. Kleinman, D. Democratizations of Science and Technology. In *Science, Technology, and Democracy*; Kleinman, D.L., Ed.; State University Press of New York: Albany, NY, USA, 2000; pp. 139-166.
91. Aerni, P.; Bernauer, T. Stakeholder attitudes toward GMOs in the Phillipines, Mexico and South Africa: The issue of public trust. *World Dev*. **2006**, *34*, 557-575.
92. Dawson, J.C.; Goldberger, J.R. Assessing farmer interest in participatory plant breeding: Who wants to work with scientists? *Renewable Agric. Food Syst.* **2008**, *23*, 177-187.
93. Glenna, L.L.; Welsh, R.; Lacy, W.B.; Biscotti, D. Industry perceptions of university-industry relationships related to agricultural biotechnology research. *Rural Sociol.* **2007**, *72*, 608-631.