An agroecosystem is constrained by environmental possibility and social choices, mainly in the form of government policies. To be sustainable, an agroecosystem requires production systems that are resilient to natural stressors such as disease, pests, drought, wind and salinity, and to human constructed stressors such as economic cycles and trade barriers. The world is becoming increasingly reliant on concentrated exporting agroecosystems for staple crops, and vulnerable to national and local ...
Sustainability and Innovation in staple crop production in the US Midwest
running title: Staple crop innovations in the US

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Abstract

An agroecosystem is constrained by environmental possibility and social choices, mainly in the form of government policies. To be sustainable, an agroecosystem requires production systems that are resilient to natural stressors such as disease, pests, drought, wind and salinity, and to human constructed stressors such as economic cycles and trade barriers. The world is becoming increasingly reliant on concentrated exporting agroecosystems for staple crops, and vulnerable to national and local decisions that affect resilience of these production systems. We chronicle the history of the US staple crop agroecosystem of the Midwest region to determine if sustainability is part of its design, or could be a likely outcome of existing policies particularly on innovation and intellectual property. Relative to other food secure and exporting countries (e.g., Western Europe), the US agroecosystem is not exceptional in yields or conservative on environmental impact. This has not been a trade-off for sustainability, as annual fluctuations in maize yield alone dwarf the loss of caloric energy from extreme historic blights. We suggest strategies for innovation that are responsive to more stakeholders and build resilience into industrialized staple crop production.

Keywords: agrobiodiversity; intellectual property; market concentration; biotic and abiotic stress; genetic modification
Introduction

Producing food is the major activity of humankind (IAASTD, 2009). About half the producers, mostly poor, farm to feed themselves and their families and they produce 20% of the world’s food (Fess et al., 2011). Despite this distributed production, much of the world’s plant-sourced calories come from massive monocultures, such as the maize and maize/soy rotation systems of the United States Midwest.

The world’s largest producer of maize (Zea mays L., corn) is the US. This has been true since the UN Food and Agriculture Organisation (FAO) started keeping production records in 1961. Despite its size, the US agroecosystem has had historical periods of very low on-farm genetic diversity (Box 1). For example, by the late 1960s, 80-85% of the commercial maize plantings in the US were based on a single innovation, the (“T”) cytoplasm (Adams et al., 1971, Ullstrup, 1972).

The low level of agrobiodiversity in the world’s staple crops is a continuing concern. Already in 1996, the UN FAO proclaimed that in “China, of the nearly 10,000 wheat varieties in use in 1949, only 1,000 remained in the 1970s...In the United States, 95 per cent of the cabbage, 91 per cent of the field maize, 94 per cent of the pea, and 81 per cent of the tomato varieties cultivated in the last century have been lost” (FAO, 1996).

The scale of production of particular kinds of crops in the ‘breadbaskets’ – countries that produce significant quantities of food especially for export - influences what seed is available to other farmers, including organic and poor farmers (Pingali and Pandey, 2000, Enjalbert et al., 2011). The breadbaskets also are used by other industries. In the case of maize, for example, a large number of industries are dependent upon it and also
benefit from the substantial agricultural subsidies for maize production in the US (Pollan, 2007b). The Corn Refiners Association (CRA, 2007) lists products from “household needs” such as briquettes and trash bags, “personal care” such as deodorant, “pharmaceuticals” such as aspirin and antibiotics, “tobacco”, “fuel” (alcohol), “paste and adhesives” “textiles” including dyes, “chemicals” such as organic solvents, acids and agrochemicals and “building supplies” such as cardboard and fiberglass. Up to 25% of the products in the average American grocery store may contain maize (Pollan, 2007a).

Given the concentration of power in the breadbaskets for the major crops, how they set their innovation policies is relevant well beyond their borders. The modern US agroecosystem was built on a long history of public breeding programs as the source of germplasm innovation (e.g. Fernandez-Maizeejo and Caswell, 2006). In the 19th Century, agriculture in the US was based on seed saving and exchanges between a larger number of small farmers. Seed quality certification schemes appearing around 1915 provided a role for commercial breeders. Breeders were small businesses that amplified seed stock from varieties produced by the public sector. Then as now, public breeding programs and seed exchanges (coupled with on-farm experimentation and adaptation of germplasm) were critical sources of genetic variety (Vigouroux et al., 2011).

Importantly, they have and continue to provide farmers and gardeners with choices (Steinberg, 2001, Howard, 2009). The knowledge required to select and save seed, and the infrastructure for exchanges, are also social resources that if lost may be difficult to re-establish (Howard, 2009). In a future of climate change, public breeding and in situ conservation are likely to be fundamental to the survival of billions of people (McIntyre et al., 2011, Campbell, 2012).
Seed saving and exchanges persisted and thrived under intellectual property (IP) rights frameworks that dominated agriculture in the US for most of the 20th Century. As these were replaced with strict IP instruments, such as patents and patent-like plant variety protections appearing in the 1980s and 1990s, seed saving and exchanges disappeared (Mascarenhas and Busch, 2006, Glenna and Cahoy, 2009).

The transition from a farmer-led, breeder-supported system of developing crops to the current breeder-controlled innovation varied in pace in a crop-dependent manner. One of the first crops to make this transition was maize. Both the US Plant Patent Act of 1930 and especially the emergence of a commercial hybrid maize industry around the same time initiated a contraction of the maize seed industry (Committee on Genetic Vulnerability of Major Crops, 1972, Fernandez-Maizeejo and Caswell, 2006). Hybrid maize varieties effectively replaced open pollinated varieties from the US commercial agroecosystem by the 1960s (Committee on Genetic Vulnerability of Major Crops, 1972, Kutka, 2011). This transition to hybrid varieties is associated with a significant increase in yields over the period and beyond.

Hybridization can substitute for law-based IP instruments to retain ownership when the commercial traits do not uniformly transmit from hybrids to the next generation and the seed would not reveal its parentage; hybridization thus has been called the ‘biological patent’ (see discussion in Glenna and Cahoy, 2009). These two kinds of instruments for controlling varieties, one biological and the other legal, drove a conversion in the US industry from mainly small scale specialist breeders into ever larger but fewer commercial breeders (Fernandez-Maizeejo and Caswell, 2006). Patents, such as applied to genetically modified (GM) cultivars, and patent-like plant
variety protections as introduced in the International Union for the Protection of New Varieties of Plants (UPOV) convention of 1991 (Heinemann, 2007, Heinemann, 2009), are accelerating these trends.

In contrast, other important crops were much slower to transition to a concentrated breeder model. For example, until recently the US was still a world leader in seed saving and exchanges with up to 45% of the soybean (*Glycine max* (L.) Merr.) and 50% of the cotton crop coming from home-grown seed in 1982, and over 30% of soybean still recycled into the early 1990s (Fernandez-Maizeejo and Caswell, 2006, Mascarenhas and Busch, 2006). Seed saving and exchanges in these crops ended when they became available as GM cultivars and came under the control of patents in the 1990s (Heinemann, 2007, Howard, 2009). A combination of highly restrictive material transfer agreements (MTAs) (Glenna and Cahoy, 2009), and the 1994 amendment to the Plant Variety Protection Act (1970), outlawed seed saving and exchanges. The 1995 Supreme Court ruling in *Asgrow v. Winterboer* extended the ban to varieties developed before the 1994 Plant Variety Protection Act.

Breeder concentration may lead to loss of agrobiodiversity. Previously, the US National Academies of Science associated a loss of agricultural diversity with the cause of the southern maize leaf blight epidemic of 1970 (Committee on Genetic Vulnerability of Major Crops, 1972). That epidemic is a textbook example of the dangers of monoculturalisation coupled with high genetic uniformity and an indication that an agroecosystem is not sustainable.
We examine both historical and ongoing patterns of innovation in the US to see how the lessons carefully laid out by the highest scientific body of the country have been incorporated into practice.

Agricultural biodiversity includes surrounding biota and inclusion or exclusion of crop types and livestock (Frison et al., 2011, Jackson et al., 2012). It is much more than just the genetic diversity of crop plants. However, our focus is on US staple crop agrobiodiversity, particularly maize, augmented with insights from other large scale monoculture agroecosystems of wheat (*Triticum aestivum* L.), cotton (e.g., *Gossypium hirsutum*) and soybean. As the world comes to acknowledge that agriculture is not sustainable as currently practiced (IAASTD, 2009), there is need for a concept of innovation backed by an incentive system that yields agricultural sustainability.

2. Materials and Methods

Maize, rapeseed, soybean and cotton yield data was obtained from the United Nations Food and Agriculture Organisation (UN FAO) FAOSTAT database for the United States, Canada and the total group Western Europe (Austria, Belgium-Luxembourg, France, Germany, Netherland, Switzerland). The FAOSTAT began reporting statistics in 1961 and was current to 2010 at time of writing (2011 for wheat). For 2011 and 2012, additional yield statistics and projections were obtained from the United Stated Department of Agriculture, the Canadian Canola Council, and the Monitoring Agricultural Resources (MARS) Unit of the European Commission Joint Research Centre. Using R version 2.12.2 (R Development Core Team, 2011), we conducted an ANCOVA to test whether yield differed significantly among years, location (Europe or the US),
percentage of GM used, or any of the interactions. To identify the model with the best fit to the data, we used an Akaike's Information Criterion (AIC) based approach (Brunham and Anderson, 1998, Anderson, 2008) to compare all possible models including different combinations of independent variables and their interactions. The best fitting model included year, location and the interaction between year and location as independent effects.

3. Results and Discussion

An agroecosystem is constrained by environmental possibility and social context. To what degree is the North American agroecosystem meeting the dual demands of production and sustainability? We approach an answer to this question examining several metrics relevant to achieving a sustainable and adequate food supply. First, we consider whether the biotechnology chosen by the American farmer is optimising yield. Second, is the American agroecosystem achieving greater outcomes in lessening its impact on the environment, as might be indicated in reducing use of inputs such as pesticides? Third, we ask whether the social context created through policies on innovation and IP, and government subsidy programs are delivering greater resilience. Finally, we consider whether prevailing policies are adequate to meet future human resource needs.

*The North American agroecosystem: setting the technology standard?*

First the yields of maize and rapeseed were compared in North American and Western European (W. Europe) agroecosystems because these agroecosystems are of equal maturity and have similar access to sophisticated biotechnological and IP options, and
are constrained by a similar latitude and operate in the same growing season (Licker et al., 2010). We mainly focused on where different choices in biotechnologies were made. A significant difference between the two agroecosystems is the virtual absence of GM crops in our group of 6 W. European countries. In contrast, the adoption of GM soybeans, maize, rapeseed (*Brassica napus* L., canola) and cotton in the North American agroecosystem has reached near saturation. According to the industry site GMO Compass (Anon, 2011), the proportion of GM rapeseed reached 82% in the US by 2007 and 95% in Canada by 2009. In the US, GM maize reached a reported 88% by 2011, GM soybeans 94% by 2011, and GM cotton 94% by 2012 (USDA, 2012a).

Starting with maize, how has the commitment to GM crops benefitted the US agroecosystem? Maize is a dominating crop for the US Midwest and a significant crop for W. Europe. Between 1961 and 1985 the US produced on average approximately 5,700 Hg/Ha more maize per year than did W. Europe. By the mid-1980s there was a significant change in yield in our comparison countries (Figure 1). Between 1986 and 2010, W. Europe's yield averaged 82,899 Hg/Ha, just slightly above US yields of 82,841 Hg/Ha (Table 1). Comparing W. Europe to the US for the entire period 1961 to 2010 (Figure 1), the average yields were not significantly different (ANOVA: F_{1,98} = 0.53; P=0.47). These results suggest that yield benefits (or limitations) over time are due to breeding and not GM, as reported by others (Gurian-Sherman, 2009), because W. Europe has benefitted from the same, or marginally greater, yield increases without GM. Furthermore, the difference between the estimated yield potential and actual yield, or 'yield-gap', appears to be uniformly smaller in W. Europe than in the US Midwest (Licker et al., 2010). Biotechnology choices in the form of breeding stock and/or management
techniques used in Europe are as effective at maintaining yield as are germplasm/management combinations in the US.

When we tested whether yield significantly differed between W. Europe and the US in the period from 1961-2010 taking the significant annual increase in yields both in W. Europe and the US into account (ANCOVA: \( t = 20.205, P = 0.0001 \)), we found that the US had marginally significantly higher yields than Europe (ANCOVA: \( t = -2.091, P = 0.04 \)). However, we also found that the interaction between year and location was significant (ANCOVA: \( t = 2.074, P = 0.04 \)), indicating that the slope in yield increase by year is slightly steeper in W. Europe than the US from 1961 to 2010 (Figure 1). This shows that in recent years W. Europe has had similar and even slightly higher yields than the US despite the latter's use of GM varieties.

During the period 1985-2010, the US average maize yield was 82,504 Hg/Ha. Adding the known yield for 2011 and the projected yield for 2012 (USDA, 2012e) raises the US average to 82,577 Hg/Ha. W. Europe averaged 82,306 Hg/Ha from 1985-2010. Yield data for 2011 and 2012 projections for each of the W. European comparison countries were not yet available. However, 2011 yields for maize were trending upwards rather than following the US. The 5 countries France, Germany, Netherlands, Belgium and Austria averaged 111,700 Hg/Ha (MARS, 2012), up from 107,000 in 2010 (FAOSTAT). For this collection of W. European countries, 2012 projections were for average to above average yields of maize (MARS, 2012).

Although GM maize varieties have been in commercial production in the US for 17 of the 27 years, the linear regression of maize yield in W. Europe from 1985-2010 (\( y = 1156x \)
+ 66699, \( R^2 = 0.75 \)) again shows that the slope of increase per year is steeper in W. Europe than the US \( (y = 1053.4x + 67302, \ R^2 = 0.55) \).

While the bad luck of weather variations, such as two contiguous years of water stress in the US, can overwhelm the subtle contributions of a generally good technology, the variance in yields of the two agroecosystems provides an indication of their inherent resilience to stress. We therefore calculated coefficients of variance (CV) to measure the year-to-year variability of the agroecosystems. As the mean yields increase in both agroecosystem over the 50 year period from 1961-2010, we could not simply calculate CVs from average means and standard deviations. Hence, we instead obtained means and standard deviations of the residuals (a measure of annual variability) of the linear regressions (of the maize yield increase in the US and W. Europe from 1961-2010) to determine CVs. The CV for W. Europe was 0.11, lower than the 0.14 measured for the US. This shows that the annual variation in yield is greater for the US than W. Europe, indicating again that the US system is moving to a less resilient and reliable stewardship of its maize agroecosystem.

**Rapeseed and wheat**

Consistent with what is observed for maize, the yield gap appears to be increasing for Canada, the other earliest adopter of GM crops, for rapeseed. The average yields of rapeseed for Canada have always been lower than W. Europe’s, by an average of 11,000 Hg/Ha between 1961 and 1985, and an even larger average difference of 17,300 Hg/Ha between 1986 and 2010, the period when Canada moved to GM and Europe did not.
Likewise, wheat yields have been consistently higher in W. Europe than in the US, on average by 31,400 Hg/Ha from 1961-2011 (Figure 2). While wheat yields significantly increase over time in both countries (ANCOVA: $F_{1,98} = 610.525, P < 0.0001$), the increase per annum was significantly higher in W. Europe than the US (ANCOVA: $F_{1,98} = 44.674, P < 0.0001$). GM wheat is not used in either agroecosystem. This again indicates that yield gains are not dependent on GM biotechnologies and that the combination of biotechnologies used by W. Europe is demonstrating greater productivity than the combination used by the US.

A trade-off of yield and pesticide use?

Essentially wherever GM is used at significant levels it is through cultivation of crop varieties tolerant of glyphosate-based herbicides. A significant minority, the “Bt” plants, express an insecticide. The use of herbicide tolerant plants introduced two significant changes into the US agroecosystem. First was direct spraying of glyphosate-based herbicides on the staple crop during its cultivation, and second was the quantity of the herbicide that could be used in a growing season. Between 1996 and 2011, overall herbicide use increased by 239 million kilograms (527 million pounds) (Benbrook, 2012). Provided that the in-plant produced insecticide is not counted, then GM Bt crops led to a reduction in insecticide use of 56 million kilograms (Benbrook, 2012). When the in-planta insecticide is added back, there is no net reduction in insecticide application (Benbrook, 2012). There nevertheless may be benefits to substituting the protein pesticides produced by the plants for the same amount of agrichemicals that might otherwise be used, although this seems to be primarily a benefit in cotton and not maize (Marvier et al., 2007, Benbrook, 2012).
The short term reduction in insecticide use reported in the period of Bt crop adoption appears to have been part of a trend enjoyed also in countries not adopting GM crops (Figure 3). Thus, reductions attributed to GM crops (Fedoroff, 2012) are in question. In 2007 (the latest FAOSTAT figures available for the US) US chemical insecticide use was down to 85% of 1995 levels by quantity of active ingredient, and herbicide use rose to 108% of 1995 levels. Meanwhile, similar if not more impressive reductions have been achieved in countries not adopting GM crops. By 2007 France had reduced both herbicide (to 94% of 1995 levels) and chemical insecticide (to 24% of 1995 levels) use, and by 2009 (the latest FAOSTAT figures available for France) herbicide use was down to 82%, and insecticide use down to 12%, of 1995 levels. Similar trends were seen in Germany and Switzerland.

*Is farm and innovation policy producing sustainability?*

In the US, two dominant policies affecting staple crop agroecosystems are innovation (through development and licensing of intellectual property, such as seed germplasm) and public subsidies (Quist *et al.*, 2013). These are part of the complex social context that guides agricultural goals, including sustainability goals.

The US type subsidy program promotes monocultures directly and indirectly because it is based on acreage of the crop; so larger acreages attract more subsidies (Lin, 2011). Moreover, the larger and more uniform the crop the more amenable it is to cost reductions through planting and harvesting mechanization and simplified pest control (Lin, 2011), one of the primary drivers of GM traits in the staple crops (Heinemann,
In a self-reinforcing cycle, public subsidies for GM crop production are increasing maize farm sizes (Key and Roberts, 2007, Harwood, 2010).

The public subsidy for the US farming sector is extremely influential. It is estimated at $277.3 billion (EWG, 2012) for just the years 1995-2011 (and even larger for Europe, Heinemann, 2009). The 2008 farm bill authorizes a further $US290 billion in subsidies to 2012 (Harwood, 2010). Maize subsidies in the US are estimated at $US81.7 billion from 1995-2011 (EWG, 2012) and $US51 billion from 1995-2002 (Lin, 2011). As a result of subsidies, the US sells maize on the world market at 73% of its production cost, wheat at 67%, sugar at 44% and milk at 61% (Harwood, 2010). The cost to developing countries is $US17 billion per year (Harwood, 2010), and thus subsidies potentially undermine emergence of more sustainable production systems.

Failure to appropriately diversify on-farm germplasm has historically caused food production, supply and price uncertainty. One of the most illustrative historic examples is the southern maize leaf blight epidemic in the US maize agroecosystem (Box 1). What has happened since the blight to both germplasm diversity on a large commercial scale, and actual on-farm diversity?

As a measure of innovation as a driver of on-farm diversity, we used seed catalogue data provided by the Monsanto Company to the US Department of Justice’s antitrust investigation of the seed industry (Whoriskey, 2009) to estimate trends in germplasm diversity for American farmers (Table 2). The number of cultivars on offer in seed catalogues may not represent the actual genetic diversity available, even if it may be a possible measure of product innovation (Magnier et al., 2010).
In the case of maize, the number of cultivars belies the true genetic diversity on offer. Writing of the southern maize leaf blight epidemic in 1970, Adams et al. said that the “genetic base of maize presently grown in the Maize Belt of middle America is much narrower than the diversity of names and numbers of hybrids would suggest” (p. 1069 Adams et al., 1971).

The most dramatic effect on maize agrobiodiversity predates the modern variety (Vigouroux et al., 2011). Nevertheless, most of the developed countries derive all of their diversity from this narrow germplasm and the effect of economic and IP policy on innovation in agriculture is continuing to narrow the germplasm (Shi, 2009, Vigouroux et al., 2011). “A single variety, ‘Reed Yellow Dent’, contributes 47% of the gene pool used for the creation of hybrid varieties” (p. 452 Vigouroux et al., 2011). The “proprietary nature of commercial maize hybrids [in use in the US maize belt] complicates determination of the composition and diversity” (p. 1687), but the germplasm is limited to only about 7 founding inbred lines (Pollak, 2003, Lee and Tracy, 2009), with 36% of varieties registered from 1996-2005 coming from just the line B73 (Mikel, 2008). Similar trends are seen for soybeans (Mikel et al., 2010).

Over the period 2005-2010, the total number of maize cultivars decreased by 1780, or 20%. Soybean choices also decreased 13%, from 4437 to 3844. Changes in cotton choices were much smaller in absolute terms, probably because of the contraction in commercial seeds that predate 2005 (Fernandez-Maizeejo and Caswell, 2006). In percentage terms the reduction in choice is still severe, falling by 18% (Table 2).
What cultivars or diversity of cultivars are found on-farm? Consistent with others, we could find no published information to answer this question (Mikel et al., 2010, NRC, 2010). Total diversity contained in-situ (e.g., in the many small farms, if different) or ex-situ (e.g., in gene banks) does not capture either the vulnerability of the system nor predict how quickly it can recover from a disaster (Committee on Genetic Vulnerability of Major Crops, 1972). For example, in the wake of the 1970 epidemic it was more difficult for farmers to source seed to plant in 1971 (Ullstrup, 1972).

The consequences of any mass loss of productivity in the US agroecosystem are apparent. Consider that the southern maize leaf blight epidemic in the US resulted in a decrease of the maize crop from 119,056,000 tonnes in 1969 to 105,471,000 tonnes in 1970, well below the 143,421,000 tonnes produced in 1971 (FAOSTAT). The actual yield in 1970 was 45,439 Hg/Ha, considerably less than in 1969 (53,908 Hg/Ha) and in 1971 (55,297 Hg/Ha). The trend line drawn from 1961-1969 (Figure 4) predicted a yield of 54,408 Hg/Ha in 1970 \((y = 1807.3x + 36335)\). With 23,211,600 Ha sown in 1970, the projected production was 126,289,673 tonnes resulting in an actual shortfall of 20,818,673 tonnes from expected. Estimating the Calories (kcal) in 1 tonne of maize at 888,889 (USDA, 2009b), the loss was equivalent to 18.5 trillion \((18.5 \times 10^{12})\) Calories.

Do we now have sufficient diversity to avoid such massive losses? Adverse high temperatures during maize pollination in 2010 in the US caused a decline in yields from 2009 and the downward trend due to weather continued in 2011 to a level not seen since 2005 (NASS, 2011, NASS, 2012, USDA, 2012b). By August 2012, the USDA projection was for a maize crop of 10.8 billion bushels and a yield of 123.4 bushels/acre
(76,173 Hg/ha USDA, 2012e), the lowest since 1995 and a yield common in the 1980s (FAOSTAT).

Likewise for soybean, the projected 2012 US yield of 40.5 bushels/acre is the second lowest since 2003 (27,000 Hg/ha USDA, 2012d). US cotton is projected to have its second lowest yield since 2003 at 785 lbs/acre (8,800 Hg/ha USDA, 2012d).

The annual variance in maize yields is, just from weather disturbances, surpassing the magnitude of the 1970 epidemic. The difference between projected (14.8 billion bushels USDA, 2012c) and expected (10.8 billion bushels USDA, 2012e) in 2012 is $1 \times 10^8$ metric tons, or 89 trillion Calories. In contrast, the 2003 drought in Europe cost about 5 trillion Calories based on a yield midway between 2002 and 2004 yields.

While the world makes more calories for food now than it did in 1970, the proportion of dependence on maize has only increased, making each maize calorie lost even more important. Total Calories from crops (excluding alcohol) were 2335/capita/day in 1970 and 2728/capita/day in 2007 (latest statistics from FAOSTAT). The proportion of Calories from maize grew from 4% in 1970 to 5% in 2007, making the world no less dependent on maize for food now than in 1970. Moreover, US law requires 40% of the maize crop to be used to make biofuel (BBC, 2012), further increasing the relative value of maize calories in 2012 vs. 1970.

As in 1970, there is a heavy reliance on a narrowing germplasm in the major food, feed and fuel crops of a particularly powerful exporting agroecosystem, and the variance in losses due to biotic and abiotic stress are indicating instability rather than sustainability.
In contrast, varietal diversity on-farm is making significant contributions to rice yield, decreased losses to disease, lower pesticide application rates and higher farmer incomes in other agroecosystems. Researchers in China have documented such benefits when combining hybrid rice and traditional varieties (Leung et al., 2003, Zhu et al., 2005). Other studies show that mixed species intercropping - that is maize with tobacco, maize with sugarcane, maize with potato and wheat with broad beans - increased yields of least one partner and increased overall yields and reduced disease (Li et al., 2009).

A trade-off for human resources?

While the staple crop germplasm diversity has been declining, so has the number of farms. According to the United States Department of Agriculture, the number of farms in the US peaked at just under 7 million in 1935. The farming system covered approximately 1 billion acres and farms averaged 155 acres (~63 Ha, USDA). While the size of the agroecosystem remains about the same, the number of farms had fallen to just over 2 million by 2007 (USDA, 2009a).

The story is even more interesting when it comes to maize. The median US maize farm was 450 acres by 2002 (Hoppe et al., 2007), with the fewer large farms in excess of 2000 acres (>810 Ha, USDA, 2009a).

Today the US produces 12-13+ billion bushels of maize a year, or ~⅓ of the world's supply (NASS, 2009). Maize was harvested for grain from 86.2 million acres in 2007 (Table 58 of USDA, 2009a) and 79.6 million acres in 2009 (NASS, 2010). In 2007, 83% of the land for maize grain was in farms over 500 acres (200 Ha), 62% in farms over 999
acres and 35% in farms over 2000 acres (Table 58 of USDA, 2009a). Approximately 60 million acres, or 69% of the acreage, was concentrated in Large or Very Large Family Farms, defined as having sales in excess of $250,000 and $500,000, respectively (USDA, 2009a). These 114,000 farms comprised 33% of the farms growing grain maize but produced 71% of the crop and nearly 80% of the crop value. In short, in the American maize agroecosystem, \( \frac{1}{3} \) of the farms produce \( \frac{4}{5} \) of the value and \( \frac{2}{3} \) of the crop.

In addition to fewer farmers, there is less allowable on-farm capacity to contribute to innovation through breeding. This is due to the monopolization of the US seed sector (WorldBank, 2007, Glenna and Cahoy, 2009, Domina and Taylor, 2010, Fitzgerald, 2010, Kalaitzandonakes et al., 2010, NRC, 2010). The seed market concentration is not because of GM crops, but as many major crops are now almost exclusively GM in the US agroecosystem, this transition to GM must be compatible with the forces that have been concentrating the seed market.

This is evidenced in the failure of either the biological patent or the pre-1994 plant variety protections to concentrate the market in maize and soybeans anywhere near today's levels. For example, in 1980, 70% of the area planted in soybeans used seeds developed by the public sector and by 1997, 70-90% of planted area used private sector seeds (Fernandez-Maizeejo and Caswell, 2006). By 2007, the area planted in public seeds fell to 0.5% (Shi, 2009). With the introduction of GM crops came the ability to apply dual restrictions of contract law through the use of the MTA and the patent, the most restrictive IP instrument in agriculture.
As a result, seed prices are rising. The rise in prices is a function of the strict intellectual property control permitted for GM seeds and the resultant seed market concentration. “Relative to 1994, seed prices have risen by 140% while the index of other input prices has increased by 80%. The highest price increase in the United States has been in cotton” (Zilberman et al., 2010).

Traditionally, farmers could participate in generating on-farm diversity through their own participation as breeders, but this option has been outlawed in the US and other countries adopting stricter IP instruments since the 1990s. Loss of farmer experimentation may reduce future resilience under climate change, natural disasters or as an outcome of conflict (Mascarenhas and Busch, 2006, Mercer and Perales, 2010, Frison et al., 2011).

Unfortunately again, this specialisation in the farm workforce is not translating into a yield or security benefit. There is no indication that the contraction of germplasm through the use of ‘biological patents’ and restrictive IP instruments are increasing resilience in this early period of climate change (Jaradat et al., 2010). The impact of climate change on global yields of maize, wheat and barley have been seen since the 1980s, and since 1990 for soybean (Lobell and Field, 2007).

Ironically, the US agroecosystem used to be one of the world’s largest seed saving and exchange cultures. Critically, as demonstrated in the soybean sector, seed saving and exchanges were a source of useful new germplasm for the largest American farmers (Mascarenhas and Busch, 2006). The US trend belies the move to build new knowledge from the interaction of breeders and farmers in developing countries which shows
promise for raising yields and reducing damaging inputs into agriculture (Fess et al., 2011). Encouragingly, there are examples of attempting to address the concentration of resources, knowledge and germplasm in wheat through on-farm dynamic management for in situ conservation in Europe (Enjalbert et al., 2011).

Conclusion

Reviewing the parameters of yield, pesticide use, germplasm diversity and human resources of the US staple crop agroecosystem demonstrates that lessons provided by past technology-derived disasters, such as the southern maize leaf blight epidemic (Committee on Genetic Vulnerability of Major Crops, 1972), still have to be learned. The US (and Canadian) yields are falling behind economically- and technologically-equivalent agroecosystems matched for latitude, season and crop type; pesticide (both herbicide and insecticide) use is higher in the US than in comparator W. European countries; the industries of all types that are supplying inputs to the farmer are becoming more concentrated and monopolistic (Fuglie et al., 2012) and these tendencies correlate with stagnation or declines in germplasm diversity (Welsh and Glenna, 2006, Howard, 2009, Domina and Taylor, 2010). Farm number is decreasing and scale increasing, concentrating and narrowing farming skills.

The choice of GM-biotechnology packages in the US agroecosystem has been the stark contrast with W. European patterns of biotechnology use. Notwithstanding claims to the contrary (e.g. Derbyshire, 2011), there is no evidence that GM biotechnology is superior to other biotechnologies (all “technological applications that use biological systems, living organisms, or derivatives thereof, to make or modify products or processes for a
specific use”, IAASTD, 2009) in its potential to supply calories (Heinemann, 2009, IAASTD, 2009).

It may be argued that the high adoption rates of GM crops in the US, and before that maize hybrids, is an indication that the market is responding to farmers’ needs. Among a number of potential counterviews to this position is that suppliers of products, as well as research, are not neutral participants in establishing needs. Cultivation and management knowledge is sold to farmers as a ‘technology package’ along with selected GM germplasm (Glover, 2010, Quist et al., 2013). As Kutka (2011) points out, it was not obvious even into the 1940s that maize hybrids would be superior to open pollinated varieties. It was a combination of non-scientific factors as well as the market success of some hybrids that eclipsed further development, determining their fate perhaps before the science was mature. Early protagonists of hybridization were able to frame the future with hybrids as scientific, whereas a future with open pollinated varieties was not.

The US has particular ambitions for maize where it expects to maintain its global command of supply, and to continue to make maize indispensible. The US expects dependence on US maize to grow for the foreseeable future, with record high exports of maize by 2021 (USDA, 2012b). The US share of the world trade in maize is expected to grow to 55% in contrast to wheat at only 16% (USDA, 2012b).

With these ambitions, there may be more expectation from the global community that the US is operating sustainably. Global interest extends to considerations of the resilience of the US agroecosystem to disease and abiotic stress. Producing food is an
essential activity, and the ability to produce food is a global strategic asset. “No country is self-sufficient in plant genetic resources; all depend on genetic diversity in crops from other countries and regions” (FAO, 2009). Resilience can be increased using a diverse germplasm (Mulumba et al., 2012). Moreover, the full climatic potential of a crop depends on the combination of genetics, nutrition and management (Licker et al., 2010).

As the world becomes increasingly dependent upon maize for both materials and food needs, is the farmer decision-making process adequately democratic? The US National Academy of Sciences (NAS) did not seem to think so 40 years ago when it said:

“The resources of all countries should be regarded as part of an interdependent habitat rather than merely as possible sources of supply; and our national policy should therefore conform to the principles of conduct adopted by the community of nations in a common effort to protect the human habitat and its resources” (NAS, 1974).

*GM is a symptom*

The problem is not in this case GM crops *per se*. For example, the genetic diversity of the commercial maize germplasm is not uniquely narrow. Even on farm, it is comparable or even more diverse than other major commercial crops such as rice, soybeans, wheat and cotton (Mikel, 2008), and there is no significant contribution to rice and wheat cultivars from genetic engineering. There is also reason to believe that the amount of diversity is sufficient to maintain yields even in the face of most unknown pathogens that might emerge (Mikel, 2008). However, the emerging combination of stresses under
climate change, and the opportunities for new pathogens, is unprecedented (Lin et al., 2008).

Nonetheless, GM crops are not a solution, in part because they are controlled by strict IP instruments. Despite the claims that GM might be needed to feed the world, we found no yield benefit when the US was compared to W. Europe, other economically developed countries of the same latitude which do not grow GM crops. We found no benefit from the traits either.

GM crops have maintained or increased US pesticide use relative to equally advanced competitors. The pattern and quantities unique to the use of GM-glyphosate-tolerant crops has been responsible for the selection of glyphosate-tolerant weeds, with estimates of resistant weeds on between 6 and 40 million hectares in the US {Benbrook, 2012 #115; Owen, 2011 #83; Waltz, 2010 #84; Heap, 2013 #123}. The use of Bt crops is associated with the emergence of Bt resistance and by novel mechanisms in insect pests (Lu et al., 2010, Waltz, 2010, Benbrook, 2012, Zhang et al., 2012).

The diversity of the germplasm is not increasing under the commercial sector in the US and under prevailing government innovation incentives created through IP instruments or public subsidies. Critically, it appears that the essential diversity being used by the major seed houses was introduced by now defunct public sector breeding programs (Mikel, 2008); the substitution of commercial innovation incentives has not replaced the genetic innovations built by a former applied public sector service under a different, less restrictive, innovation regime (Mikel, 2008, Wolinsky, 2010). This is linked to globally declining rates in yield growth. “The growth rate in world-average crop yields
has been slowing for nearly two decades, to some extent as a result of reduced research and development funding” (p. 18 USDA, 2012b). Innovation through reclaimed IP revenue streams has not compensated for the decrease in public good research funding.

**Future strategies**

It is possible to restate the reflections on the southern maize leaf blight epidemic of the NAS from 1972, as if it were today. “The major question the Committee on Genetic Vulnerability of Major Crops asked was, ‘How uniform genetically are other crops upon which the nation depends, and how vulnerable, therefore, are they to epidemics?’

- The answer is that most major crops are impressively uniform genetically and impressively vulnerable.

- This uniformity derives from powerful economic and legislative forces.

- The situation poses substantial challenges to scientists and to the nation” (p. 1 Committee on Genetic Vulnerability of Major Crops, 1972).

How much has changed since the NAS asked that question 40 years ago? Is it possible that such obvious lessons from 1970 would have been forgotten? There is precedent for this cycle. The NAS observed a similar period of forgetfulness preceding the southern maize leaf blight epidemic: “[T]he lesson implicit in this correlation [between genetic uniformity and susceptibility to disease], which was published in 1939, had to be learned all over again in 1970” (p. 37 Ullstrup, 1972).

Powerful economic and legislative forces continue to drive uniformity. The US has concentrated its agricultural innovation policy on ever more narrow and restrictive IP
rights instruments since the 1970 epidemic, and has not addressed the issue of narrowing genetic diversity in the major staple crops or management practices.

What can be done to both invigorate innovation in crop breeding from both the seed producing companies and farmers, grow agrobiodiversity while maintaining or building yields, and motivate a transition from high input high vulnerability monocultures to sustainable low input high yield cropping systems?

First, annual statistics of on-farm agrobiodiversity should be collected, especially for the largest farms. These should be collected with relevant biotic and abiotic stress events to create a landscape scale picture of performance and resilience.

Second, on-farm diversity should be encouraged, perhaps by re-directing the subsidy program to support farmers transitioning to higher resilience farming practices.

Third, innovation strategies that promote long-term sustainability and yields, rather than peak quantity, should be introduced. This may require revising or inventing new intellectual property rights instruments to maintain private sector incentives, or a return to a public breeding and farm extension strategy that does not require capture of a revenue stream from licensing of IP.

In any case, change must come from more than just the technology sector. A viable roadmap for the future of agriculture was presented by the International Assessment of Agricultural Knowledge, Research and Development (IAASTD, 2009). This roadmap, and the warning from the Committee on Genetic Vulnerability of Major Crops, leave us no excuses.
Box 1: History of Southern Maize Leaf Blight Epidemic

The modern hybrid (Kutka, 2011) is the foundation of the U.S. maize/maize agroecosystem. The commercial maize prototype originated in a research field run by graduate student Donald F. Jones in 1917. By 1948, Jones combined his hybridization technology with natural “male sterile” mutants and his newly discovered “restorer” lines, thus introducing a commercial scale efficiency gain in seed stock production (Committee on Genetic Vulnerability of Major Crops, 1972).

Jones’ hybridization technology effectively drove out alternatives to hybrids and replaced them with the T cytoplasm. When this variety “was first introduced into production of hybrid seed, it obviously could not be foreseen that this type of cytoplasm carried with it hyper-susceptibility to a then unknown physiologic race of Helminthosporium maydis, the causal agent of southern maize leaf blight” (p. 39 Ullstrup, 1972). H. maydis was a specialist pathogen that threatened collapse of the maize crop in 1970. Although at the time there were other sources of food and a change in the weather in 1971 halted the spread of the pathogen, the “amount of food energy lost to disease was many times larger than that lost during the historic famine-producing epidemic of potato blight in the 1840s” (p. 39 Ullstrup, 1972). Food prices rose internationally in response to reports of the disease (Ullstrup, 1972).

Jones issued an insightful early warning about his new technology some 12 years before the epidemic, and at least 4 years before the pathogen was even described in the scientific literature:
“Genetically uniform pure line varieties are very productive and highly desirable when environmental conditions are favorable and the varieties are well protected from pests of all kinds. When these external factors are not favorable, the result can be disastrous ... due to some new virulent parasite” (reported in Committee on Genetic Vulnerability of Major Crops, 1972).

This was a lesson many years in the construction despite being anticipated decades before, but early warnings were not heeded (Committee on Genetic Vulnerability of Major Crops, 1972, Ullstrup, 1972). According to a US National Academies of Science report, “[t]he technology that resulted in the great epidemic of maize blight in 1970 passed through several stages over nearly six decades” (p. 7 Committee on Genetic Vulnerability of Major Crops, 1972). Of the late lesson, the Committee asked retrospectively and possibly prophetically (p. iii): “Why was [the epidemic] not foreseen? Where did the technology go awry?”

Acknowledgements
We thank Brigitta Kurenbach and Jason Tylianakis for constructive comments on the manuscript.
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Figure 1. United States and Western European maize yields and variability over the period 1961 to 2010. Authors’ calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

Figure 2. United States and Western European wheat yields over the period 1961 to 2011. Authors’ calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

Figure 3. Comparative trends in pesticide use in the U.S. and France. The use is normalised to reported amount of arable land in each year. Authors’ calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

Figure 4. United States maize yields over the period 1961 to 1969. Authors’ calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).