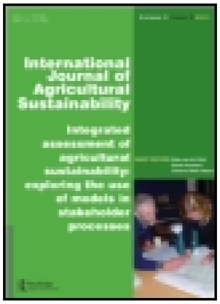

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Jack A. Heinemann [a b], Melanie Massaro [b c], Dorien S. Coray [a b], Sarah Zanon Agapito-Tenfen [b d] & Jiajun Dale Wen [e]

[a] School of Biological Sciences, University of Canterbury, Christchurch, New Zealand

[b] Centre for Integrated Research in Biosafety, University of Canterbury, Christchurch, New Zealand

[c] School of Environmental Sciences, Charles Sturt University, Albury, NSW, Australia

[d] Crop Science Department, Federal University of Santa Catarina, Florianópolis, Brazil

[e] Third World Network, Kuala Lumpur, Malaysia

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Sustainability and innovation in staple crop production in the US Midwest

Jack A. Heinemann[a,b]*, Melanie Massaro[b,c], Dorien S. Coray[a,b], Sarah Zanon Agapito-Tenfen[b,d] and Jiajun Dale Wen[e]

[a]*School of Biological Sciences, University of Canterbury, Christchurch, New Zealand;* [b]*Centre for Integrated Research in Biosafety, University of Canterbury, Christchurch, New Zealand;* [c]*School of Environmental Sciences, Charles Sturt University, Albury, NSW, Australia;* [d]*Crop Science Department, Federal University of Santa Catarina, Florianópolis, Brazil;* [e]*Third World Network, Kuala Lumpur, Malaysia*

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 United States staple crop agroecosystem of the Midwest region to determine whether 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; biotic and abiotic stress; genetic modification; intellectual property; market concentration

Introduction

Producing food is the major activity of humankind (IAASTD 2009). About half the producers, mostly poor, do farming to feed themselves and their families; 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 US Midwest.

The world's largest producer of maize (*Zea mays* L., corn) is the United States. This has been true since the UN Food and Agriculture Organization (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 United States were based on a single innovation, the ('T') cytoplasm (Adams *et al*. 1971, Ullstrup 1972).

*Corresponding author. Email: jack.heinemann@canterbury.ac.nz

Box 1 History of southern corn leaf blight epidemic

The modern hybrid (Kutka 2011) is the foundation of the US 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 (National Research Council, 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 corn leaf blight' (Ullstrup 1972, p. 39). *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' (Ullstrup 1972, p. 39). 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 National Research Council, 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 (National Research Council, 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 corn blight in 1970 passed through several stages over nearly six decades' (National Research Council, Committee on Genetic Vulnerability of Major Crops 1972, p. 7). 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?'

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 2001, Enjalbert *et al.* 2011). The breadbaskets are also 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 United States (Pollan 2007b). The Corn Refiners Association (CRA 2007) lists products from 'household needs' such as briquettes and trash bags, 'personal care' such as deodorants, 'pharmaceuticals' such as aspirin and antibiotics, 'tobacco', 'fuel' (alcohol), 'paste and adhesives', 'textiles' including dyes, to 'chemicals' such as organic solvents, acids and agrochemicals and 'building supplies' such as cardboard and fibreglass. 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 programmes as the source of germplasm innovation (e.g. Fernandez-Cornejo and Caswell 2006). In the nineteenth century, agriculture in the

United States 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. Commercial breeders were small businesses that amplified seed stock from varieties produced by the public sector. Then, as now, public breeding programmes 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 United States for most of the twentieth 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 (National Research Council, Committee on Genetic Vulnerability of Major Crops 1972, Fernandez-Cornejo and Caswell 2006). Hybrid maize varieties effectively replaced open pollinated varieties from the US commercial agroecosystem by the 1960s (National Research Council, 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-Cornejo 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, 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 United States 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 (e.g. *Gossypium hirsutum*) crop coming from home-grown seed in 1982, and over 30% of soybean still recycled into the early 1990s (Fernandez-Cornejo 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 a loss of agrobiodiversity (Jacobsen *et al.* 2013). Previously, the US National Academies of Science associated a loss of agricultural diversity with the cause of the southern corn leaf blight epidemic of 1970 (National Research Council, Committee on Genetic Vulnerability of Major Crops 1972). That epidemic is a textbook example of the dangers of monoculturalization 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 United States 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 the US staple crop agrobiodiversity, particularly maize, augmented with insights from other large-scale monoculture agroecosystems of wheat (*Triticum aestivum* L.), cotton and soybean. As the world comes to acknowledge that agriculture is not sustainable as currently practiced (IAASTD 2009, Kahane *et al.* 2013), there is need for a concept of innovation backed by an incentive system that yields agricultural sustainability.

Materials and methods

Maize, rapeseed (*Brassica napus* L., canola), soybean and cotton yield data were 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, Netherlands and Switzerland). The FAO 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 States Department of Agriculture (USDA), 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 2012), we conducted an analysis of covariance (ANCOVA) to test whether the yield differed significantly among years, location (Europe or the United States), 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-based approach (Burnham 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.

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 optimizing 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 programmes 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. European) 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 six W. European countries. In contrast, the adoption of GM soybeans, maize, rapeseed 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 United States by 2007 and 95% in Canada by 2009. In the United States, 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 United States 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 United States yields of 82,841 hg/ha (Table 1). Comparing W. Europe with the United States for the entire period 1961–2010 (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 United States.

When we tested whether the yield significantly differed between W. Europe and the United States in the period from 1961 to 2010 taking the significant annual increase in yields both in W. Europe and the United States into account (ANCOVA: $t = 20.205$, $P = 0.0001$), we found that the United States 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

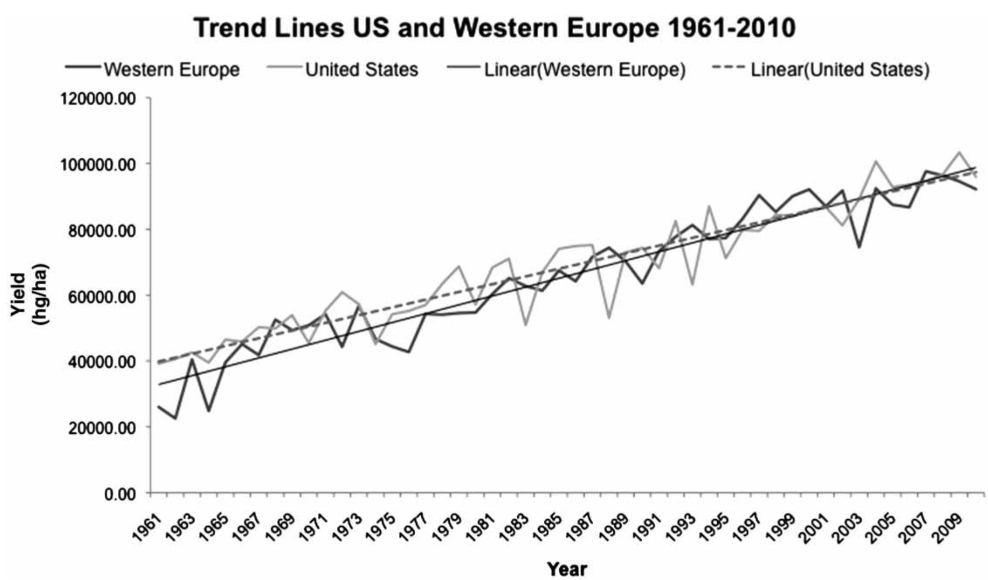

Figure 1. United States and Western European maize yields and variability over the period 1961–2010. Authors' calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

Table 1. Yield in two cropping systems over time in different regions.[a]

Agroecosystem	Crop	Average yield (hg/ha)
United States 1961–1985	Maize	54,379
Western Europe 1961–1985	Maize	48,681
United States 1986–2010	Maize	82,841
Western Europe 1986–2010	Maize	82,899
Canada 1961–1985	Rapeseed	10,489
Western Europe 1961–1985	Rapeseed	21,481
Canada 1986–2010	Rapeseed	14,588
Western Europe 1986–2010	Rapeseed	31,885

[a]Authors' calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

year is steeper in W. Europe ($y = 1344.2x + 31512$, $R^2 = 0.92084$) than the United States ($y = 1173.8x + 38677$, $R^2 = 0.89093$) from 1961 to 2010 (Figure 1). This shows that in recent years W. Europe has had similar and even slightly higher yields than the United States despite the latter's use of GM varieties.

During the period 1985–2010, W. Europe maize yields averaged 82,306 hg/ha. 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 United States. The five 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). In contrast, the United States average maize yield was 82,504 hg/ha from 1985 to 2010. Adding the known yield for 2011 and the projected yield for 2012 (USDA 2012e) raises the United States average to 82,577 ha/hg. However, it lowers the slope of the linear regression ($y = 1106.5x + 39861$, $R^2 = 0.8619$), projecting an even more severe downward trend in yields compared to W. Europe.

Although GM maize varieties have been in commercial production for most of the measured period since 1985, the linear regression of maize yield in W. Europe from 1985 to 2010 ($y = 1156x + 66699$, $R^2 = 0.75$) again shows that the slope of increase per year is steeper in W. Europe than the United States ($y = 1053.4x + 67302$, $R^2 = 0.55$).

Unfortunate weather variations, such as two contiguous years of water stress in the United States, can overwhelm the subtle contributions of a generally good technology; however, the overall variance in yields of the two agroecosystems provides an indication of their inherent resilience to stress. We therefore calculated coefficients of variance (CVs) to measure the year-to-year variability of the agroecosystems. As the mean yields increase in both agroecosystems over the 50-year period from 1961 to 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 United States and W. Europe from 1961 to 2010) to determine CVs. The CV for W. Europe was 0.11, lower than the 0.14 measured for the United States.

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 (Table 1). The average yields of rapeseed for Canada have always been lower than W. Europe's, by an average of 11,000 hg/ha between

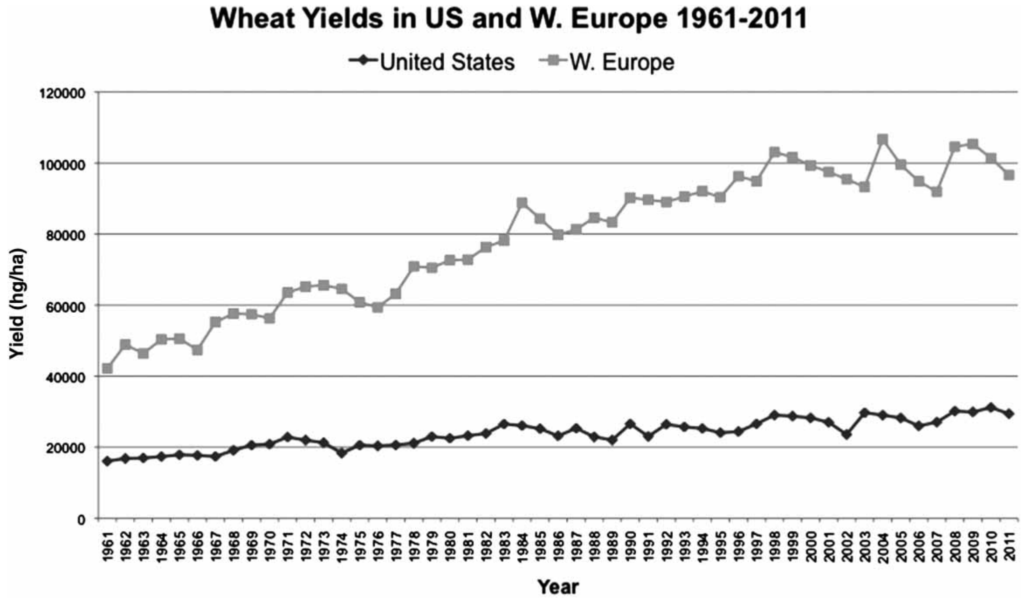

Figure 2. United States and Western European wheat yields over the period 1961–2011. Authors' calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

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 United States, on average by 31,400 hg/ha from 1961 to 2011 (Figure 2). While wheat yields significantly increased 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 in the United States (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 United States.

A trade-off of yield and pesticide use?

Essentially wherever GM is used at significant levels it is through the 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 the 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).

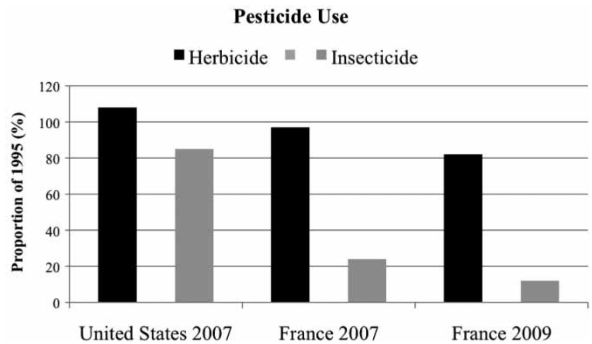

Figure 3. Comparative trends in pesticide use in the United States and France. The use is normalized to reported amount of arable land in each year. Authors' calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

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 United States) US chemical insecticide use was down to 85% of 1995 levels by quantity of active ingredients, 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 was down to 12% of the 1995 levels. Similar trends were seen in Germany and Switzerland.

Is farm and innovation policy producing sustainability?

In the United States, 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 programme 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 2009). 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 US$290 billion in subsidies to 2012 (Harwood 2010). Maize subsidies in the United States are estimated at US$81.7 billion from 1995 to 2011 (EWG 2012) and US$51 billion from 1995 to 2002 (Lin 2011). As a result of subsidies, the United States 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 US$17 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 (Kahane *et al.* 2013). One of the most illustrative historic examples is the southern corn 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 corn leaf blight epidemic in 1970, Adams *et al*. said that the 'genetic base of corn presently grown in the Maize Belt of middle America is much narrower than the diversity of names and numbers of hybrids would suggest' (Adams *et al*. 1971, p. 1069).

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 *et al*. 2009, Vigouroux *et al.* 2011). 'A single variety, "Reed Yellow Dent", contributes 47% of the gene pool used for the creation of hybrid varieties' (Vigouroux *et al*. 2011, p. 452). The 'proprietary nature of commercial corn hybrids [in use in the US maize belt] complicates determination of the composition and diversity' (Mikel 2008, 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 to 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-Cornejo 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

Table 2. Data from seed catalogues available to US farmers 2005 and 2010.[a]

Crop	Number in 2005	Number in 2010	Percent change (2005–2010)	Ratio of choice[b] 2005	2010
Corn					
Traited (GM)	5695	6079	+6.7	57%	17%
Conventional	3226	1062	−67		
Soybean					
Traited (GM)	3731	3501	−6.2	19%	10%
Conventional	706	343	−51.4		
Cotton					
Traited (GM)	114	95	−16.7	17%	15%
Conventional	19	14	−26.3		

[a]Data: authors' calculations. Source: Monsanto (http://www.monsanto.com/newsviews/Pages/monsanto-submission-doj.aspx#i). Accessed date 10 September 2011.
[b]Conventional/traited.

neither capture the vulnerability of the system nor predict how quickly it can recover from a disaster (National Research Council, 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 corn leaf blight epidemic in the United States 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 to 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 (18.5×10^{12}) calories.

Do we now have sufficient diversity to avoid such massive losses? Adverse high temperatures during maize pollination in 2010 in the United States 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, 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 (8800 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 1×10^8 metric tonnes, or

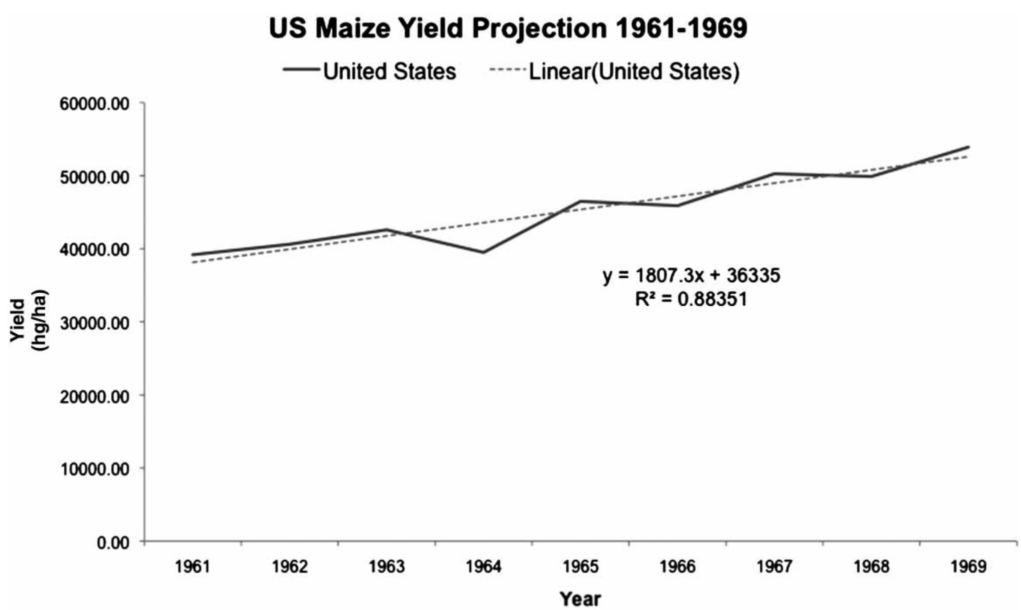

Figure 4. United States maize yields over the period 1961–1969. Authors' calculations based on data derived from FAOSTAT (http://faostat3.fao.org/).

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 is 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 at 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, the number of farms declines as well. According to the USDA, the number of farms in the United States peaked at just under 7 million in 1935. The farming system covered approximately 1 billion acres and farms averaged 155 acres (~63 ha, Hoppe *et al*. 2001). 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 United States produces 12–13+ billion bushels of maize a year, or ~1/3 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, were 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, 1/3 of the farms produce 4/5 of the value and 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-Cornejo and Caswell 2006). By 2007, the area planted in public seeds fell to 0.5% (Shi *et al*. 2009). Along 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 United States 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 specialization in the farm workforce is not translating into a yield or food security benefit. There is no indication that the contraction of germplasm through the use of 'biological patents' and restrictive IP instruments is 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 has 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 corn leaf blight epidemic (National Research Council, 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 United States 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 is increasing, concentrating and narrowing the farming skills. Annual variations in yield, which not only indicate low resilience of the agroecosytem but also can fuel dramatic price changes in agricultural markets, are more severe in the United States than in W. Europe.

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, Jacobsen *et al.* 2013).

It may be argued that the high adoption rates of GM crops in the United States, 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 United States has particular ambitions for maize where it expects to maintain its global command of supply, and to continue to make maize indispensible. The United States expects dependence on US maize to grow for the foreseeable future, with record high exports of maize by 2021 (USDA 2012b). The United States 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 United States 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, Jacobsen *et al.* 2013).

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 (NRC 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 United States 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 United States (Waltz 2010, Owen 2011, Benbrook 2012, Heap *et al.* 2013). 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 United States 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 programmes (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' (USDA 2012b, p. 18). 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 corn leaf blight epidemic of the NAS from 1972, as if it were today. 'The major question the National Research Council, 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' (National Research Council, Committee on Genetic Vulnerability of Major Crops 1972. p. 1).

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. A similar period of forgetfulness preceded the southern corn 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' (Ullstrup 1972, p. 37).

Powerful economic and legislative forces continue to drive uniformity (Jacobsen *et al.* 2013). The United Staes 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 programme 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.

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