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Genetic diversity and interdependent crop choices in agriculture[☆]

Geoffrey Heal[a,*], Brian Walker[b], Simon Levin[c], Kenneth Arrow[g], Partha Dasgupta[e], Gretchen Daily[d], Paul Ehrlich[d], Karl-Goran Maler[f], Nils Kautsky[h], Jane Lubchenco[i], Steve Schneider[d], David Starrett[g]

[a] *Columbia Business School, Columbia University, Uris Hall, 3022 Broadway, New York, NY 10027-6902, USA*
[b] *CSIRO, Canberra, Australia*
[c] *Department of Ecology & Evolutionary Biology, Princeton University, Princeton, NJ, USA*
[d] *Department of Biological Sciences, Stanford University, Stanford, CA, USA*
[e] *Faculty of Economics, Cambridge University, Cambridge, UK*
[f] *Beijer Institute of Ecological Economics, Stockholm, Sweden*
[g] *Department of Economics, Stanford University, Stanford, CA, USA*
[h] *Department of Systems Ecology, Stockholm University, Stockholm, Sweden*
[i] *Department of Zoology, Oregon State University, Corvallis, OR, USA*

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Abstract

The extent of genetic diversity in food crops is important as it affects the risk of attack by pathogens. A drop in diversity increases this risk. Farmers may not take this into account when making crop choices, leading to what from a social perspective is an inadequate level of diversity.

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[*] Corresponding author. Tel.: +1-212-854-6459; fax: +1-212-316-9219.

E-mail address: gmh1@columbia.edu (G. Heal).

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1. Trends in genetic diversity in agriculture

Are we deploying sufficient genetic diversity in agriculture? The level of genetic diversity that characterizes commercially important crops and animals is a matter of considerable concern, as it is generally agreed that access to genetic diversity has been and remains important in maintaining and increasing agricultural productivity. There are economic and epidemiological reasons to believe that the varietal choices made by farmers may lead to less genetic diversity in agriculture than is desirable from a social perspective, implying that policy interventions may be needed to ensure that we choose an appropriate level of diversity. Analyzing why we may systematically choose too little diversity is the main theme of this paper. However, before exploring these issues we review briefly the evidence on what is happening to genetic diversity in agriculture.

Some commentators have suggested that we may have experienced a decline in genetic diversity of commercial crops and animals. They attribute this to the destruction of the native habitats of many breeds and varieties, to the domestication and ensuing development of genetically uniform varieties and breeds, and to farmer and consumer preferences for certain breeds or varieties.[1] Another contributory factor is said to be the consolidation of the seed grain industry globally, leading to a more limited choice of seed varieties. At the same time, there has been widespread adoption of the same high-yield varieties of common food crops in many countries, as a part of the green revolution. (Porceddu et al., 1988) As an illustration, China currently possesses over 50 unique pig breeds, but many of these are becoming endangered as they are replaced with Western breeds. Porceddu et al. (1988) identify three waves of genetic erosion, the first beginning in the 19th century in Europe with the advent of the early plant breeders, the second in the mid-20th century, associated with a massive effort to improve productivity in non-industrialized countries through breeding for varieties with short stature and disease resistance, and a third associated with the push for uniformity (for example, using “shuttle breeding” to endow high yielding varieties with photoinsensitivity, allowing them to be grown in widely different parts of the world). The most successful examples of such centralized breeding institutes are Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) in Mexico and International Rice Research Institute (IRRI) in the Philippines (Marshall, 1977).

Further evidence for this suggestion is provided by Hammer et al. (1996), who analyzed the differences between collecting missions in Albania (1941 and 1993) and in south Italy (1950 and the late 1980s) and claimed high losses in genetic variability: levels of genetic erosion of 72.4 and 72.8%, respectively. In India, rice varieties have declined from an estimated 400,000 before colonialism to 30,000 in the mid-19th century with several thousand more lost after the green revolution in the 1960s; also Greece is estimated to have lost 95% of its broad genetic stock of traditional wheat varieties after being encouraged to replace local seeds with modern varieties developed by CIMMYT (Lopez, 1994). (Lopez also quotes a boast by Stalin to Churchill: “We have improved beyond measure the quality of our wheat. We used to sow all varieties, but now we only cultivate the Soviet prototype. Any other cultivation than that is prohibited nation-wide.”)

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[1] See Committee on Agriculture Science and Technology (2003).

A rather different perspective is provided by Smale (1997, 1998a,b) and Wood and Lenne (1997). Smale studies the trends in bread wheat varieties in use since the start of the green revolution. She tests two propositions—one that the green revolution caused genetic erosion and the second that it caused an increase in genetic vulnerability. These are significant parts of the cases developed in the studies cited in the previous paragraphs. Smale notes that a reduction in the number of varieties in use does not necessarily imply a reduction in genetic diversity, as there is no clear mapping from a reduction in the number of varieties to a loss of genetic material: indeed, she observes, some new varieties may be crosses that bring new genetic material into the commercial population even in the face of a drop in a count of varieties. She also cites evidence that over the 20th century the dominance of commercial bread wheats by a small number of varieties decreased, and that some of the land races no longer cultivated are still maintained in seed banks, and indeed have contributed genetic material to currently-used varieties.

Smale also criticizes the argument that a reduction in the number of varieties is increasing vulnerability to disease, an important part of the arguments of those who argue that we should be concerned about loss of genetic diversity. She cites evidence that modern varieties of wheat are less vulnerable to most traditional wheat diseases than their predecessors—this being one of the reasons why they have been adopted widely by farmers. Smale also observes that modern plant breeders aim for polygenic resistance to pathogens, which is intrinsically more durable and stable than the monogenic resistance that characterized early plant breeding. The loss of diversity associated with the introduction of the most resistant genotypes does, however, carry with it the potential for loss of resiliency at the level of the system as a whole.

The US National Research Council (1993) looking into this issue, concluded that the pattern is complex: various components of genetic vulnerability are going up, and others down, simultaneously in different parts of the world and for different crops. Overall, the Committee concludes (p. 80): “For major crops in developed countries, varietal turnover and the number of varieties planted have increased since 1972, indicating that the overall level of genetic vulnerability may have decreased. The genetic basis of elite germplasm, however, was found to be shallow because of extensively shared ancestry and limited use of exotic germplasm.” The summary goes on to specify priorities for reducing genetic vulnerability.

2. The role of genetic diversity

What is at stake in this discussion? The key point is that a loss of genetic diversity may lead to significant risks for food supplies. A pathogen that attacks the predominant commercial variety of a food crop can inflict immense costs on society. The classic example of this is the Irish potato famine of the 19th century. More recently, the loss of a significant fraction of the Asian rice crop to the grassy stunt virus[2] illustrates the same point—the extreme vulnerability of a geographically extensive and genetically homogeneous crop to damage by a well-adapted predator. Once a pathogen attacks any part of such a crop, it can spread

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[2] Myers (1997).

rapidly and extensively through a host to which it is well adapted with no natural barriers. In 1970 in the USA, the southern corn leaf blight epidemic resulted in enormous losses; this was considered to be a man-made epidemic caused by excessive homogeneity of the USA's tremendous maize hectarage (Browning, 1988). Other examples include the coffee rust epidemic in Ceylon in the 1870s, the tropical maize rust epidemic in Africa in the 1950s and the blue mould epidemic on tobacco in the USA and Europe in the 1960s (Marshall, 1977).

International trade can enhance these risks. The rapid movement of cargoes, animals and plants internationally means that once a pathogen occurs anywhere it can travel fast and poses a threat to populations far distant. The spread of foot and mouth disease in Europe illustrates the rapid international spread of a pathogen in the face of massive attempts to prevent this. The spread of the glassy sharpshooter to California is another example.

Not only does the genetic homogeneity of populations raise the cost of a pathogen outbreak should it occur, but it also increases the probability of such an outbreak in the first place. The distribution of pathogens by type is not exogenously given but is influenced by the distribution of host types. Pathogens evolve and adapt to the available hosts. Increasing the scale of a host will increase the probability of a pathogen evolving that is well suited to that host. We can think of the expected loss (risk) from a pathogen epidemic as a function of two variables, the probability of an epidemic and the likely cost of an epidemic given that one occurs. Formally, $L = P(E)C(E)$, where L is the expected loss from an epidemic, $P(E)$ the probability of an epidemic and $C(E)$ the cost of an epidemic. Both magnitudes on the right of this equation are increased by genetic homogeneity—this increases the probability of an epidemic (by increasing the selective pressure on the pathogen to overcome host resistance) and also the cost of one should it occur (by facilitating rapid spread). L is, therefore, likely to increase non-linearly in the degree of homogeneity. Furthermore, genetic homogeneity also serves to increase $P(E)$ by increasing the susceptible pool for a pathogen that can overcome resistance, thereby increasing the rate of spread. Indeed, epidemiological models typically imply that there is a threshold susceptible population size, below which a pathogen cannot spread at all; introducing diversity, therefore, could reduce the susceptible pool for any pathogen low enough that no outbreak is possible, or at least reduce the probability. The simplest example represents the rate of change of the infectious population I as $\mathrm{d}I/\mathrm{d}t = bSI - kI$, where S is the number of susceptible plants, bSI the rate of new infections, and kI is the death rate of infected plants. If $S < kI$, any introduction of a novel pathogen will die out monotonically.

3. Genetic diversity and risk management

In growing food, as in many other areas, society faces a risk–return trade off. It can enhance the productivity and average yield of food crops at the cost of greater risk, measured by a higher standard deviation of their yields. One illustration of this is the use of crops well adapted to particular weather patterns. If a suitable weather pattern materializes these can give yields greatly in excess of more generic crops, but if the weather pattern that is realized is not that to which they are finely tuned then their yield may be much lower than that of other options. The farmer faces a higher peak yield, and a higher yield in the normal weather conditions for his region, in exchange for poorer outcomes in less normal weather patterns.

Striking the right balance between risk and return is important: given that many people live at or near subsistence, the consequence of crop failure can be catastrophic. With little or no slack in food supplies in poor countries, society has to watch carefully the risk of a major disruption. At the same time, there is a risk in not pursuing every opportunity to expand food supplies, the risk that the population will outgrow food supplies in some regions. The risks associated with genetic uniformity have been recognized for over half a century and have given rise to attempts to conserve crop diversity, both in situ and ex situ, with arguments in favor of both. In Bush (2000), case studies of crop diversity illustrate that present levels of diversity are the outcome of farmers' needs and preferences, on the one hand, and the increasing availability of a limited number of high yielding varieties on the other—often encouraged by government. Bellon (1996), in an analysis of maize landraces in southern Mexico, found that even though new high yielding varieties and commercial support were available, farmers nevertheless maintained a complex population of landraces because no single variety could satisfy their five main concerns; environmental heterogeneity effects, resistance to pests and pathogens, risk management, culture and ritual, and diet. Browning (1988), in a review of the use of diversity, concludes that diversity is the only defense against the unknown.

There are reasons to think that farmers may be making the wrong risk–yield trade off from the perspective of society in reducing genetic diversity in order to raise yields, and specifically that they are choosing too much risk. The overall level of genetic diversity in agriculture is the outcome of millions of varietal choices made by individual farmers across the world. If they all choose similarly then society as a whole has little genetic diversity in its crops. Each farmer, when choosing a crop or animal variety, will seek what for him is the most appropriate balance between higher average return and greater risk, indicated by greater variability of the yield (see Fig. 1). Farmers will always want to choose

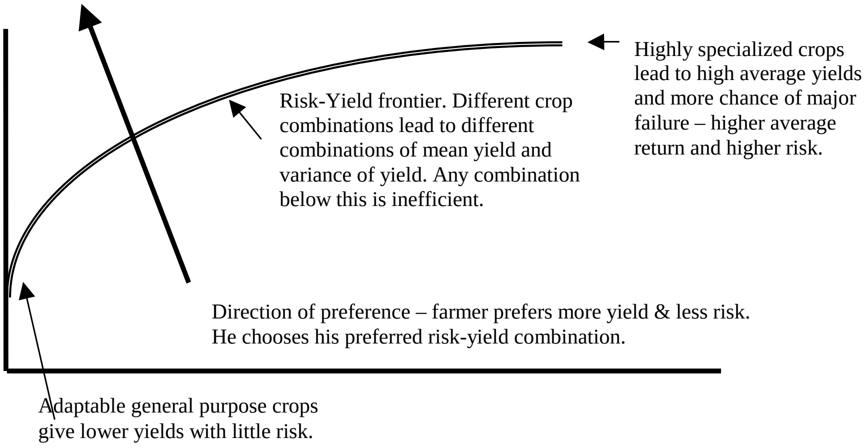

Fig. 1. The risk–yield frontier.

crop combinations on the risk–yield frontier, and exactly where on this they choose will depend on their tolerance for risk. By way of illustration, those with reserves to fall back on, or those with crop insurance, will be willing to use more risky combinations than those who are liable to starve if their crops fail. When making these choices, farmers will not in general consider the implications of their choices for the overall pattern of diversity and the implications that this has for the risks that society as a whole faces. Nor will a farmer necessarily assess accurately the risks that he personally will face as a result of his choices.

The key point here is that the risk that each farmer faces as a result of his crop choice is not fully under his control. Compare two hypothetical situations, one where a farmer plants his 100 ha with crop variety X and no one else within 500 km plants variety X, and a second one where every farmer within 500 km also plants variety X. Our hypothetical farmer faces a greater risk of pathogen damage to his crops in the second case than in the first. If a pathogen for variety X arrives anywhere within 500 km, there is a higher probability that it will spread to him in the second case than in the first, as it will find hosts and thrive anywhere within 500 km. In addition, with an area of at least 3.142×500^2 km^2 planted with variety X, there is now a chance that somewhere in this region there will occur a mutation of an existing organism that produces a pathogen for variety X. This chance, as we have noted, is larger, the greater the area planted with variety X.

We can model these issues using a simple game-theoretic framework. Assume for simplicity that there are two farms, F_1 and F_2, and two crop varieties V_1 and V_2. Let p_i be the probability of a severely damaging infestation of crop V_i ($i = 1$ or 2) when it is planted by only one farmer and let q be the probability of an infestation crossing from one farm to the other if both use the same variety (for simplicity, we take q to be independent of the common variety). If the crops are different there is no risk of an infestation moving from one farm to another. If a crop is successful then a farmer's income is Y (independent of the crop again, mainly to simplify notation) and if there is an infestation this is reduced by L, the loss from the infestation. There are obviously four possibilities that we need to consider, represented in the following payoff matrix where the rows are F_1's strategy and the columns F_2's strategy. The cases are: both farms use V_1, both use V_2, and each uses a different variety (V_1/V_2 and V_2/V_1). If each uses a different variety then the expected payoffs in the two cases are $(Y - p_1L, Y - p_2L)$ and $(Y - p_2L, Y - p_1L)$ where the first entry is farm 1's return and the second farm 2's return. (These are the lower left and upper right entries in the payoff matrix.) If both farms plant V_1 (the top left corner in the payoff matrix) then each has the same payoff, $Y - p_1L - (1 - p_1)p_1qL$. Conversely, if both plant V_2 then their common payoff is $Y - p_2L - (1 - p_2)p_2qL$ (bottom right). In the case when both plant V_1 then p_1L is the expected loss from an infestation originating on the farmer's own land and $(1 - p_1)p_1qL$ is the expected loss from an infestation arising on the other farmer's land (probability p_1), transferring across farms (probability q), all conditioned on there not having been an infestation already originating from the home plot $(1 - p_1)$.[3] We can represent these payoffs in the conventional matrix, where the rows are F_1's strategy and the columns F_2's strategy:

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[3] This is an illustration of the interdependent security problem discussed by Kunreuther and Heal (2002) and Heal and Kunreuther (2002).

	V_1	V_2
V_1	$Y - p_1L - (1 - p_1)p_1qL, \ldots$	$Y - p_1L, Y - p_2L$
V_2	$Y - p_2L, Y - p_1L$	$Y - p_2L - (1 - p_2)p_2qL, \ldots$

Recall that all p's and q are probabilities so that they are between zero and one. From this matrix it is easy to show that there will be a Nash equilibrium at which both choose different crops if $p_1 < p_2(1 + q) - q(p_2)^2$ and $p_2 < p_1(1 + q) - q(p_1)^2$. For $q = 0$, these two inequalities are inconsistent. For $q > 0$, they are consistent for $p_1 = p_2$ and by continuity for an open set of p values containing the diagonal. They are consistent for:

$$q > \max\left\{\frac{p_1 - p_2}{p_2(1 - p_2)}, \frac{p_2 - p_1}{p_1(1 - p_1)}\right\}$$

So, in general, there is a set of values of p_1 and p_2 having positive measure that are consistent with a Nash equilibrium at which the two farmers choose different crops. Fig. 2 illustrates this: the region in which diversity is an equilibrium is lens-shaped and increases as q increases.

It is also possible to show that in the area outside the lens, both farms will use the same crop at a Nash equilibrium. This area satisfies the reverse inequalities to those given in paragraph above, namely $p_1 > p_2(1+q) - q(p_2)^2$ and $p_2 > p_1(1+q) - q(p_1)^2$. We can also tie this analysis back in to the risk–yield frontier considered earlier (Fig. 1). If both farmers choose different varieties then their expected incomes are $Y - p_1L$ and $Y - p_2L$ for varieties 1 and 2, respectively, and the variances of their returns are $p_1(1 - p_1)L^2$ and $p_2(1 - p_2)L^2$. If, however, both choose the same variety then the expected incomes are $Y - p_1L - (1 - p_1)p_1qL$ or $Y - p_2L - (1 - p_2)p_2qL$ depending on the common crop and the variances are $[1 - p_1 - (1 - p_1)p_1q][p_1 + (1 - p_1)p_1q]L^2$ or the same with 1 replaced

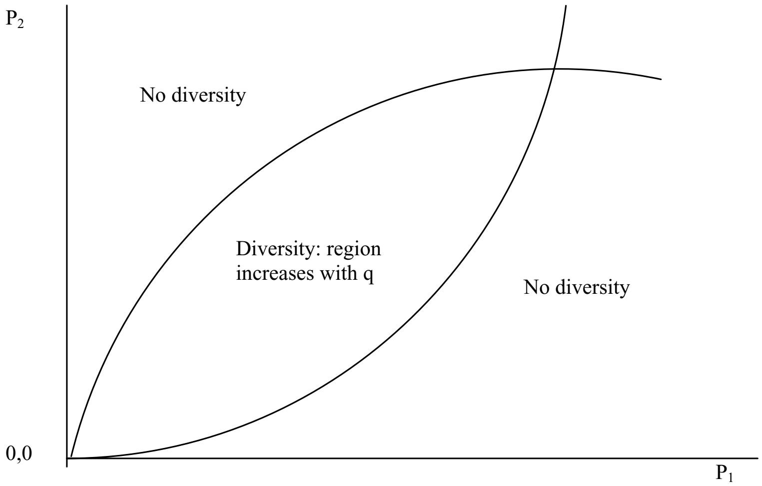

Fig. 2. How diversity at equilibrium depends on the parameters.

by 2. It is now clear that for each crop the expected return is lower and the variance of the return higher when both farmers plant it than when only one plants it. So, the risk–return frontier moves down and to the right as we move from considering an isolated farmer to a farmer who is surrounded by others choosing the same crop.

4. Policy responses

The existence of external effects between farmers implies that the overall allocation of risks in society, and indeed the overall allocation of resources, will be inefficient. The analysis of Nash equilibria above indicates that under a range of parameter values farmers will make identical choices of variety and will select too little diversity. To achieve efficiency we would need to face each farmer with a cost that indicates the extent of the external effect that he is imposing on others by making the same choice as them. The result would be that individuals would to some degree be steered away from making the same choices as their neighbors, and so the resulting level of genetic diversity in food crops and animals would be greater than at present. In terms of the diagram, we wish to expand the lens area to include all likely values of p and q.

There are several institutional mechanisms through which this could be effected. The classical responses to external effects are either to levy taxes or to redefine property rights. In the present case, the tax-based approach would require a tax that depends on choice of variety—a homogeneity tax. In practical terms, we would look for a tax rate on seeds that is higher on the more popular varieties and so provides an incentive to move to the less popular ones. Equivalently, we could think of a subsidy to the less popular varieties, bringing down their prices and again transferring demand to them (Ehrlich and Ehrlich, 1982). To the extent that the obstacles to the use of the less popular varieties are lack of knowledge and lack of access to advice and support, rather than purely financial issues, then the appropriate response would also involve increased provision of information about the use of the less popular varieties. A solution based on reform of property rights would be more complex: typically Coasian approaches to externalities have given rise to “cap and trade” mechanisms such as that used for SO_2 in the US and proposed by the Kyoto Protocol for the control of greenhouse gases. For varietal choice, such a mechanism might work by requiring permits for the use of the more popular varieties and then limiting the numbers of permits issued and making them tradable. There is currently a requirement imposed on users of *Bt* corn by its producer, Monsanto, that is a crude approximation to these measures: farmers who plant *Bt* corn are required to plant certain fraction of their land with non-*Bt* products as a way of limiting the development of pathogens that are resistant to the toxins expressed by the *Bt* genes. This way they hope to maintain the effectiveness of the *Bt* toxin as an insecticide. The use of *Bt* corn raises several issues, including the possible impacts of plant-produced toxins on wildlife and the possible loss of effectiveness of the *Bt* toxin, and this latter issue is close to those considered in this paper. Concentration of large areas under *Bt* corn will in the long run reduce its effectiveness and will also reduce the effectiveness of some of the benign insecticides traditionally used by organic farmers. There is, therefore, a social interest in crop variety, though individual farmers may find that from a private perspective their best choice is to use only the *Bt* varieties. That this problem has been recognized and is being tackled in this limited area is encouraging, and sets a precedent for the types of measures required on a larger scale.

5. Conclusions

In summary, genetic diversity in agriculture is important. Its lack can increase social vulnerability to pathogens and increase the risks that we face with our food supplies. Genetic diversity in agricultural systems is changing, and there has been a decline in traditional crop varieties and in breeds and varieties of animals. This may be associated with growing international trade in foods and in seeds. There is now perhaps an increase in the diversity of new genes included in new varieties, but the net effect of this is uncertain. A consequence of these changes is a potentially serious increased risk of food production failure. The solution lies in recognizing the risk, specifying regional goals to contain it, and facilitating appropriate institutions (or international rules) to achieve them.

Whatever the historical trends in agricultural genetic diversity, and there is some argument about these, there are strong a priori reasons to think that individual farmers will choose a degree of genetic homogeneity that is greater than is socially optimal, and that there is consequently a case for policy intervention here. This observation would not be invalidated by a flat or even increasing trend in agricultural biodiversity: in the case of an increasing trend it would imply that for a socially efficient outcome the upward trend should be even stronger. We have indicated the types of interventions that might be appropriate. The problem that we have identified has features in common with one of the problems arising from the use of *Bt* corn and the desire to maintain the effectiveness of the *Bt* toxin as an insecticide. A problem with a similar structure arises with respect to the development of antibiotic resistance in bacteria. Here, the private and social costs of the choice of an antibiotic are different, and in particular each time an antibiotic is used this imposes costs on other who might need to use it.

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