The insurance value of biodiversity
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Effects of genetic diversity versus high productivity crops on long-term agricultural performance

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Abstract

Genetic diversity is the main source of agricultural productivity rises, but declines fast as a consequence of the widespread adoption of high yielding seeds, developed on its basis. The paper tries to investigate, to what extend seed diversity is needed for continuing productivity advances and what strategies of the farmers are most profitable for different rates of pest infections, because it is known that an important percentage of annual yields are lost to pests and diseases. To this purpose, a Multi-Agent simulation model is designed, which allows to examine the performance of a model agricultural sector for different settings. The model results revealed that although seed diversity is important for long term adaptability, it is reduced more or less considerably under all circumstances. A main finding of the paper is that, unfortunately, this is not caused by irrational behaviour of the farmers. Under realistic conditions, it is most profitable to use a strategy with a significant amount of imitation, although diversity is reduced thereby. This is true, not only on the individual level, but for the whole sector as well. If society wants to maintain seed diversity, it therefore has to recur to options actively inciting the farmers to do so, e.g. by remunerating them this service.

Keywords: Crop diversity, Agrodiversity, On-farm conservation, Modelling, Multi-Agent System, Genetic Algorithm, Agricultural intensification, Genetic resources

1 Introduction

Genetic resources are the origin of agricultural production. Half the yield gains in major U.S. cereal crops in the last 70 years are attributed to genetic improvements (Day-Rubenstein et al. 2005). A considerable amount of productivity enhancements can be traced back to scientifically bred varieties with their higher performance or resistances. However, scientifically bred crops reduce the genetic variety and thereby induce the undesirable side effect of inhibiting further ameliorations. Plant breeders need diversity to adapt the crop seed to constantly changing environmental conditions. And the genetic uniformity of many modern crops makes them particularly vulnerable to evolving pests and diseases or changing weather conditions. The agricultural sector as a whole is therefore confronted with the question of balancing high current productivity against the long-term adaptability of a genetically diverse crop.

Some papers have been written about the cost-benefit aspect of biodiversity conservation or the typical common resource dilemma, the costs of maintaining diversity being often private (when it is maintained by farmer-developed varieties or the renouncement to cultivate the habitat of wild crop types) whereas benefits are public (Jackson et al. 2007, Perrings et al. 1995 or Pascual and Perrings 2007).[1] The current paper is not concerned with these issues.

An interesting approach to asses some aspects of the value of crop diversity for further agricultural production is Goeschl and Swanson (2002). Within the framework of a macroeconomic endogenous growth model they investigate the amount of R&R to develop new seed varieties that farmers would undergo under two different regimes: a benevolent social planner and individual firms. Goeschl and Swanson explain the necessity for a continuous R&D by two processes, reducing the value of current best seeds: 1. a Schumpeterian “creative destruction”, which devaluates old seed varieties as new and more productive ones are developed and 2. “adaptive destruction” by biological adaptation of pests and diseases to new crop varieties, which reduce their productivity considerably. The model is a quite interesting approach but it has some shortcomings, particularly where the actual amount of crop diversity in the system is concerned. Success of R&D in Goeschl and Swanson´s model uniquely depends on the amount of another natural factor, land, allocated to this purpose.[2] Although the allocation of scarce input factors reveals something about the importance of the corresponding production sector, such an analysis is unable to grasp the dynamic nature of the actual breeding of new crop varieties. First, land may well be important for its development, but need not necessarily be considered as opposed to final production. In fact, new seed variants are often

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[1] The benefits of agrobiodiversity are not only condsidered for agriculture, but – in a broader concept of external effects – for society as a whole, i.e. in the form of ecological services, environmental quality, recreation and aesthetic values (Jackson et al. 2007).

[2] Land in Goeschl and Swanson´s growth model being the only scarce input factor, the allocation of which between R&D and final production is the only relevant decision of this economy.

developed while planting for final production.[3] Second, and most importantly, the success of breeding new crops is by no means a purely economic process, depending mostly on investments in R&D. The main input factor in successful breeding is a diverse gene pool of existing crop seeds. As this aspect is neglected in the model, a real estimation of the value of biodiversity (claimed in the title of the paper) is not possible in this way.

The current paper tries to asses the role of genetic diversity in agricultural production by linking the potential for further developments of the crop seed directly to its current diversity. I.e., as in nature, new varieties can only be developed as modifications or recombination of existing ones. This breeding procedure is embedded in a modelling framework, in which the trade off between high present productivity and the long-term necessity of diversity becomes obvious. The model illuminates the issue by letting the right mixture evolve endogenously in a changing environment, without referring to an external cost-benefit balance. It does so by placing the economic agents in an environment which remains stable for some time but undergoes periods of change as well. Under stable conditions a fast convergence to the so far best performing variety is often the best short term solution. But even than not always. Further breeding and experimentation with diverse crops might reveal even further amendments. Its real fallacy however, is the reduction of genetic diversity which is needed as an insurance against change. The model reveals the appropriate blend of an adoption of high productivity crops and the maintenance of adaptability by sustaining a diverse gene pool. A main intention of the paper is to depict the essential amount of diversity for different rates of environmental change. Although costly at short-term, an appropriate base level of biodiversity is a crucial aspect of long-term agricultural development and its economic success.

The paper is organized as follows: Section 2 will introduce into the problem of biodiversity loss by genetically unified crops. It will cite some figures and tell some stories about the usefulness and problems of high yielding varieties (further on HYV) and it will explain how and why agrobiodiversity should primarily be conserved "in situ", i.e. on-farm. Section 3 then proposes a multi-agent modelling framework for the assessment of the value of crop diversity. This value has here been named insurance value, because crop diversity is the basis for further agricultural development in terms of variety-enhancements and pest and disease resistances – the latter making the idea of insurance probably most comprehensible. Section 4 presents and discusses the results of the model and section 5 concludes the paper.

2 Crop diversity loss and the insurance value of diversity

A considerable part of yield gains in agriculture can be directly traced back to genetic improvements of the seeds (Day-Rubenstein et al. 2005). For some periods and

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[3] This is particularly true for developing countries with their individual landraces (Bardsley 2003). It is these landraces in turn on which developed countries revert to when looking for new resistances or adaptations to difficult environmental circumstances.

countries they are immediately related with the “Green Revolution”, a widespread planting of scientifically bred crop seeds that are particularly productive. In India e.g., the yields for different cereals increased by more than 3.5 times in the 45 years between 1950 and 1995 (Bohle 1999). Marco Quinones, involved in the process of implementation of the Green Revolution in India, even claimed that wheat yields increased 6.6 times in just 31 years between 1963 and 1994 (Keller 1996).

Such advances are only possible on the basis of a diverse gene pool – which in turn is reduced as a consequence of the propagation of genetically unified HYV. Thus far, there has been no major breakdown of yields or the seed breeding industry, but that can basically be attributed to the fact that diverse seed and the connected knowledge about its characteristics is still available from developing countries. Particularly this knowledge is foremost available from on-farm use of the seeds. Although gene banks offer a possibility to store some varieties, they constitute more of an “emergency admission” than a real alternative to in-situ agrobiodiversity (Keller 1996). To begin with “only a small fraction of the world’s plant genetic resources have been collected thus far” as Day-Rubenstein et al. (2005) state in a report of the United States Department of Agriculture on the economic aspects of crop genetic resources.[4] Second, for a considerable number of varieties there are no sufficient declarations, concerning their provenance or characteristics. But even more important, storing in a genetic library is no lifetime insurance. The seeds have to be kept under very specific conditions and replanted periodically in order to maintain their regenerative capacity (Day-Rubenstein et al. 2005). Not all gene banks have the means to provide this care.[5] Finally, even well conserved seeds have not undergone natural selection and adaptation for the time slumbering in a gene bank. Some 50 years further, new diseases, they are not resistant to, might have developed and a formerly well equipped crop might die from a simple “cold”.

Thus knowing about the importance of a diverse gene pool, and particularly of on-farm conservation, world wide figures of crop diversity loss are alarming. It was estimated that Indian farmers in the 50th used more than 30.000 varieties of rice. At the end of the 20th century they used only 50 (Keller 1996). 10% of the global land area is used for intensive agriculture, 17% for extensive agriculture (Mooney et al. 2005). Considering the vast parts of the world in which industrialized agriculture is not yet possible, due to their economic poverty, these are disturbing figures. Even in Nepal, one of the purest countries of the world, 80% of the agriculturally suitable lowland areas are planted with HYV rice in intensive agriculture. The remaining 20%, where farmers still plant local varieties, must already be regarded as a lot (Jarvis et al. 2000). Only in remote mountainous regions of Nepal´s mid-hill areas, over 80% of the rice seeds are local varieties – mostly due to the fact that these are often the only ones able to survive in high altitude (Jackson 2007).

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[4] For beans e.g., an estimated 80% of all varieties are not stored (Keller 1996).

[5] After the fall of the Eastern bloc states, Czechia e.g. simply had no money to even harvest some onions and leek, they had planted for rejuvenation of the seeds (Keller 1996).

There are three major aspects responsible for this tremendous loss: 1. genetic uniformity of scientifically bred varieties, 2. an augmenting conversion from farmer-developed varieties (landraces) to scientifically bred varieties and 3. the loss of wild crop varieties, due to agricultural use of formerly uncultivated land (Day-Rubenstein et al. 2005). The first mentioned genetic homogeny is even prescribed by laws like the German Law on the marketing of seeds (Saatgutverkehrsgesetz), stating that a seed may only be marketed after having been approved as basic or certified seed, such approval requiring genetic uniformity!

So the phenomenon enhancing agricultural performance is at the same time reducing its capacities for further development. We know that crop genetic diversity is essential for a further improvement of crop seeds and even for protection of the status quo. Pests and diseases adapt to resistances and are able to infest a new seed every 5 years on average (U.S. Department of Agriculture 1990, Heisey and Brennan 1991). Once infested, annual crop losses amount to almost 30%, increasing with each year the variety is used (Oerke et el. 1994, Scheffer 1997). 1/3rd of worldwide yields are lost annually to insects, diseases and weeds (Saedler 1995). Although worldwide yields for major crops are not endangered thus far, the lack of diversity has already led to local agro-ecological problems (Bardsley 2003). Already in the 1960th, Switzerland was infested by rust epidemics on wheat, due to the extensive use of the seed “Probus”. Turkey and West Asia were recently infested in consequence of the Green Revolution that reduced wheat diversity considerably (Bardsley 2003).

In developing countries HYV are often badly adapted to local conditions. They do not support local environmental conditions like severe cold, high altitude, too much or too little rain or some local parasite. Even if their yields are higher than those of traditional landraces, the income of the farmers may decline in these countries, due to the higher costs for seed, fertilizer and pesticides (Keller 1996).[6] Another mayor problem is water. HYV are more demanding in water supply and continuity than some local varieties, adapted to droughts as well as floods, common in a lot of developing countries. But even developed countries with an industrialized agriculture can suffer from acute problems, due to monocultures and their particular nature. In 1970, the USA e.g. got through a corn disaster, because the high yielding hybrid corn with its uniform cytoplasm was an ideal breeding material for the "Northern Leaf Blight", a fungus causing a damage of several billions of dollars. A loss so tremendous, that it finished the era of hybrid production by the particularly vulnerable sterile male cytoplasm (Saedler 1995).

The uniformity of crops thus being a problem requiring their constant renewal, it is beyond doubt that agriculture depends essentially on maintenance of diverse crops, even to secure the status quo. It is with this problem in mind that the term “insurance

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[6] An evaluation of the consequences of a conversion from traditional landraces of rice to modern varieties for four villages on the Philippines e.g., established that although yields raised by over 70% between 1970 and 1981, the income of the farmers declined by half, because costs for pesticides and fertilizer tippled in the same period (Keller 1996).

value" has been chosen to illustrate the significance of crop diversity. Diverse seeds insure against losses due to the infestation of uniform seeds from diseases. They are an insurance as well in the sense that some investment in their availability has to be made. Society as a whole – or the individual farmer – has to renounce to some part of today's profits in order to insure itself against possible future losses, by planting less productive varieties on parts of the land. Baumgärtner (2007) therefore compares biodiversity with financial insurances and states that its level of maintenance also depends on the availability of the latter. When farmers can get financial insurance against yield losses – e.g. due to "natural hazards" like extreme weather conditions or parasites – or even get financial support for free after such events, they are less likely to be interested in conserving seed varieties themselves. In fact they might even be less likely to plant the most resistant seed variety if a potentially more productive variety with higher vulnerability is available. The risk is than externalized.[7] In the current paper we are not concerned with this additional quandary. Either are we concerned with an illustration or possible solutions to the dilemma of the commons, i.e. the lack of private incentives to conserve agrodiversity, when the benefits will go to the larger public. With the framework described in the following section, the paper will concentrate upon the long-term performance of agriculture under different assumptions about the speed of adoption of a unified HYV, or – to express it the other way round – different levels of maintenance of crop diversity.

3 The modelling framework

3.1 Seed varieties, yields and diseases

The framework for the following investigation is a Multi-Agent-System, based on an environmental and an agent level. On the agent level a Genetic Algorithm maps the search strategies of the agents. 50 farmer agents have the opportunity to decide which crop seed they will cultivate. The known crop varieties correspond to the different crops that are cultivated at a given time step. Seeds are only preserved in-situ, i.e. by on-farm use. This corresponds to the above mentioned insight that conservation in gene banks is very limited and problematic for several reasons. The knowledge base changes over time. The agents can try to develop new seed

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[7] Such an understanding of insurance value is close to – but not exactly congruent – with the ecologists understanding of the term "insurance effect". While the paper's interest is limited to agricultural yields, the ecological insurance effect is a somewhat broader, but on the other hand more limited concept. An ecosystem encompassing a high level of biodiversity is likely to include species that are functionally redundant, i.e. not essential for the maintenance of its structure or processes. If one of several such functionally similar species suffers from any changes or goes extinct, the other can step in and insure the stability of the ecosystem (Hooper et al. 2002). Our insurance value also protects against system breakdowns, but it does so without necessarily providing redundant (i.e. equally productive) seeds. Some of them might be, but others might be less productive and will still be regarded as insurance (in that sense the concept of this paper is broader). On the other hand, it only considers the diversity of crop seeds – not of the encompassing ecosystem, the diversity of which is also known to have positive effects on crop yields and resistance – and not the insurance effects upon this ecosystem, but solely on agricultural yields. In that sense the concept is narrower.

variants. They do so by crossbreeding known seeds or by incorporating gene traces of other known seeds. They can also imitate other agents, i.e. they plant a seed that someone else has developed. Or they decide to continue planting their current seed.

Underlying this agent level is an environmental level of potential seed yields. In this environment all possible seed variants are stored as a reference for the model itself. This yield or fitness base – common to most Multi-Agent models – is needed to attribute fitness values to the agents, but of course not known by them in advance or in its entire extent. It corresponds to the external environment in which the agents plant their seed and harvest their crop. In the exemplary model this fitness base encompasses 128 varieties and is therefore comparably small in relation to natural seed diversity as it has been e.g. for rice in India over 50 years ago. More than 30.000 varieties have been reported then (Keller 1996). On the other hand it is still larger than the remaining 50 varieties reported 10 years ago (ibid.), but probably smaller than the 60 varieties of rice reported for some communities of 10.000 people in Nepal (Khatiwada et al. 2000).[8] However, the agents searching this seed base are also relatively few, compared to the number of farmers worldwide and letting some 50 or even a few hundred agents cultivate several thousands of seed varieties would confront them with an unrealistically large search space. The main intention of the proposed framework is to investigate the effect of a fast or less fast adoption of HYVs – with the thereby induced loss of diversity – and the number of agents and seed is large enough to depict this problem.

In the model, the fitness base changes over time, due to the fact that it is known from literature, that newly developed seed variants have often better characteristics, concerning pest resistance, than former ones and that their yield is higher than theirs. On average, such a new HYV is discovered every 8 to 11 years (U.S. Department of Agriculture 1990). The fitness base of the model therefore intersperses new HYVs on a regular basis. This does not mean that these have been detected – i.e. actually invented – by the agents, but from then on they can be developed by breeders. Although this external influence on the fitness base is not entirely satisfying, it was deemed a better solution than offering the complete fitness landscape right away. In the latter case, agents could incidentally discover varieties that are much more profitable than all the ones that are currently known which does not correspond to experience. The model introduces new HYVs and their corresponding potential yield in a way that enables the whole agricultural model sector to raise their actual yields by factor five in 50 years for realistic conditions.[9] This is an average, corresponding to reports on real yield raises for different countries, following the introduction of better seed (Bohle 1999, Keller 1996). Figure 1 depicts the design of the external fitness landscape and the actual performance of the farmers in this environment. The

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[8] If such comparably small communities already have such a widespread diversity of seed variants, the total number of seeds worldwide and even in Nepal is considerably higher, although the largest part of them is only located at one or a few adjoining fields.

[9] What these conditions are, will be explained shortly. Some of the model runs reach higher growth rates, but they do so under unrealistically low disease rates and very high rates of breeding experiments which would be too costly in reality.

grey bars (with red dotted borders) represent the environment. Known to the agents are only the parts they currently inhibit. These are indicated by the dark red bars, corresponding to the planted seeds and their yield.

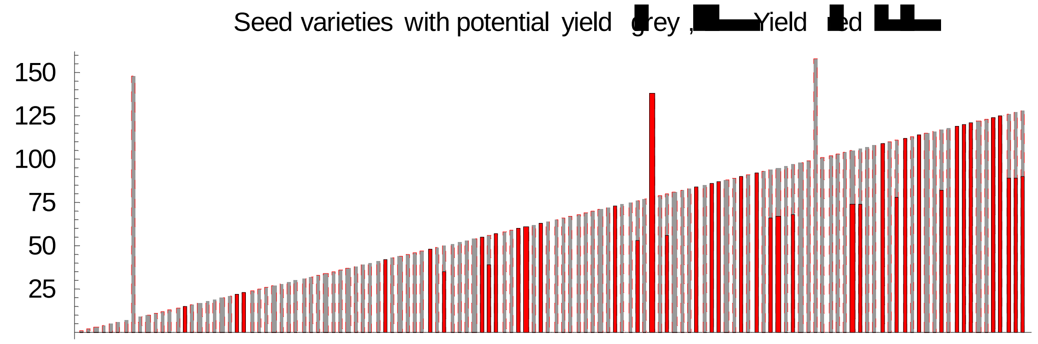

Fig. 1: Fitness base and current yield with HYVs

Note that some of the yields are lower than the underlying bar. This is caused by yield reductions due to pests and diseases. Literature reports that new HYVs are infested between 3 and 7 years after their propagation by a newly adapted pest that has overcome the resistance of the seed to formerly known pests (or been delivered with a corresponding pesticide) (Heisey and Brennan 1991). If a crop is infested, its yield reduces by almost 30% in the first year, inclining with time, if the seed is still used (Oerke et el. 1994, Scheffer 1997). The probability to be infested by pests is higher, the more farmers are using a specific variety. Particularly scientifically bred varieties are designed to resist known pests. However, if they are adopted by a large part of farmers (as is often the case with the newest HYV in the USA), parasites are more likely to adapt to them. This effect has been included into the model by enhancing the natural pest infestation probability when many agents are using the same seed. It has been tested how different levels of pest adaptation to the seed varieties infest yields. The pressure of newly introduced HYVs and yield reductions by pests on the search for new variants, have been termed “creative destruction” (going back to the Schumpeterian term) and “adaptive destruction” by Goeschl and Swanson (2002). Both are claimed to have an effect on the necessity to invent new seed varieties. The former, because it reduces the demand for formerly best practice when a better one appears, the latter because it reduces yields, particularly the ones of HYVs that are used by many farmers, making it easier for parasites to adapt. Creative destruction is not actually included in the model, as there is no separate breeding sector, fearing for its income, when competitors develop better seed. But adaptive destruction is present. Once a seed is infested, its yield may drop under the performance of formerly lower yielding varieties. Farmers are incited to change and look for better solutions.

4 Farmers and their strategies

Every agent has a certain probability (75%) to decide for a new variety in every time step that corresponds to a planting season. In the model, the following 5 behavioural strategies are investigated:[10]

- Random Search
- Recombinant Search combined with Random Search
- Recombinant Search
- Imitation with Recombinant Search
- Imitation

The last three strategies are combined with low levels of random influences, due to natural evolution. Seed that is planted on fields reproduces naturally (if it isn't one of the scientifically bred varieties that are no longer able to do so) and thereby adapts e.g. to diseases and pests or changes its characteristics and yield potential. Natural evolution is also present in the first two strategies, but the level of random influences is considerably higher there and attributed to the fact that the agents are experimenting with arbitrary changes by themselves.

Random search is a strategy without crossbreeding of varieties. Single gene traces are exchanged by others in a trial and error procedure. This strategy reminds the practice of pharmaceutical firms in the design of new products. It creates a huge amount of useless variants which is time and money consuming and therefore not always appropriate or possible.

Recombinant search corresponds to crossbreeding of know varieties. This is particularly interesting to do with seed that has already proven to be productive. When looking for varieties to crossbreed with, the farmers therefore look at their former performance.

The last pure strategy is Imitation which simply amounts to buy a known seed variant, promising high yields – the most likely strategy for farmers in industrialized countries, whereas farmers in developing countries still often develop their own varieties, due to lack of funds to buy expensive HYVs and due to the fact that they are not always well adapted to their local conditions.

When new varieties have been developed, they are not planted straightforward. In the model architecture, a new seed is tested and only adopted if it performs better than the current seed of the corresponding farmer. This amounts to the assumption that seed performance is something that is usually tested in small cultivations before

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[10] Note that so far the model has no meta search rule, deciding what strategy has to be followed under which conditions. This would be an important next modelling step. So far the different rules are just compared in their performance when applied consecutively to the whole population of agents. A more realistic assumption for the agent's behaviour would be to decide first about the best strategy under given conditions, with respect to the degree of uncertainty, the agent's knowledge, the satisfaction with current result, his attitude towards risk and his time and money constraints (Beckenbach 2005).

being planted on the main fields. A farmer only adopts a new seed if he expects higher yields than with his former one.

5 Model results: balancing high current productivity versus long-term adaptability

Different parameter settings, corresponding to different environmental conditions and agents strategies, have been tested in their influence on the yield performance of the whole agricultural sector over the whole observation time and on the development of the highest yielding variety over time. Table 1 depicts the average results over 100 runs respectively for all the different settings. Each individual run goes over 50 time steps. The values in the result boxes are the average results for the summed up yields over time and the best yielding variety at the end of the observation period. Note that the latter is not necessarily representative, as it is subject to a high degree of randomness for individual runs. However, as the values are averages for 100 runs, as for the aforementioned value, it is still interesting to look at, in addition to some exemplary time charts over the whole observation time. The main insights will be reported in the following.

Settings					**Results**	
Pest infestation	**Search mode**	**Cross Prob**	**Evol/rand Prob**	**Imi Prob**	**$\sum$ Yield**	**Highest yield at time 50**
No pestProb = 0	Random Search	0	0.14	0	**403.252**	360,1
	Recombinant + Random Search	0.75	0.014	0	**385.534**	332,1
	Recombinant Search	0.75	0.0014	0	**343.493**	289,9
	Imitation + Recombinant Search	0.75	0.0014	0.5	**387.783**	224,9
	Imitation	0.75	0.0014	1	**377.926**	226,9
Low pestProb = 0.01	Random Search	0	0.14	0	**353.892**	365,5
	Recombinant + Random Search	0.75	0.014	0	**308.795**	306,072
	Recombinant Search	0.75	0.0014	0	**284.848**	244,044
	Imitation + Recombinant Search	0.75	0.0014	0.5	**306.972**	187,418
	Imitation	0.75	0.0014	1	**285.496**	173,712
Realistic pestProb = 0.1	Random Search	0	0.14	0	**280.850**	311,562
	Recombinant + Random Search	0.75	0.014	0	**284.113**	253,452
	Recombinant Search	0.75	0.0014	0	**267.806**	226,29
	Imitation + Recombinant Search	0.75	0.0014	0.5	**297.938**	185,996
	Imitation	0.75	0.0014	1	**278.973**	163,482

Table 1: Sum of yields over 50 time steps and highest yield at time 50.
Average of 100 runs for different search modes and environmental conditions.

The influence of different rates of environmental change (adaptive destruction)

The speed with which crop seeds can be infested by pests, reducing their yield by 30% has been varied from no pest infestation (pestRed = 0) over a low infestation (pestRed = 0.01) to a realistically high pest infestation (pestRed = 0.1). The latter implying, that every 10. crop/year can be infested for “common” crops, only used by one agent. This probability is rising with the number of adopters of the seed. It reaches every 5. crop/year for 20% of adopters (which corresponds to the figures from literature for HYVs) and goes even higher if more than 20% of the farmers are planting the same variety.

In the summed up yields over all agents and all runs (i.e. the outcome of the agricultural sector over the whole observation span) the difference between no and a realistically high pest reduction rate is considerable and maps the familiar 30%.[11] Yields for the best performing strategies go from 280.850 for pestRed = 0.1 to 403.252 for pestRed = 0. The influence is also visible for the highest individual yield at the end of the observation period. Numbers for both are given in Table 1, but can also be seen in comparing average yields over time for exemplary runs. Fig. 2 shows results for a realistic pest infestation, Fig. 3 for an agriculture without diseases and parasites, the first chart being overall yield, the second one the highest yield for the respective time steps (i.e. the current HYV). For the latter, the effect is a little less discernable, because these values do not reflect how many agents already use the respective seed. New HYVs that are used by many agents, are more likely to be infested by an adapting pest but it may well be that a higher individual yield value only signifies that someone has discovered a new HYV that has not yet disseminated broadly. The figures also show how pest infestation repeatedly dents into the yields of the current HYV. As can be seen in Fig. 2, each time, a seed is infested, HYV yield go down and can only rise again after breeding has discovered a new HYV. Whereas Fig. 3 shows continuous productivity steps, rising each time a new HYV is discovered.

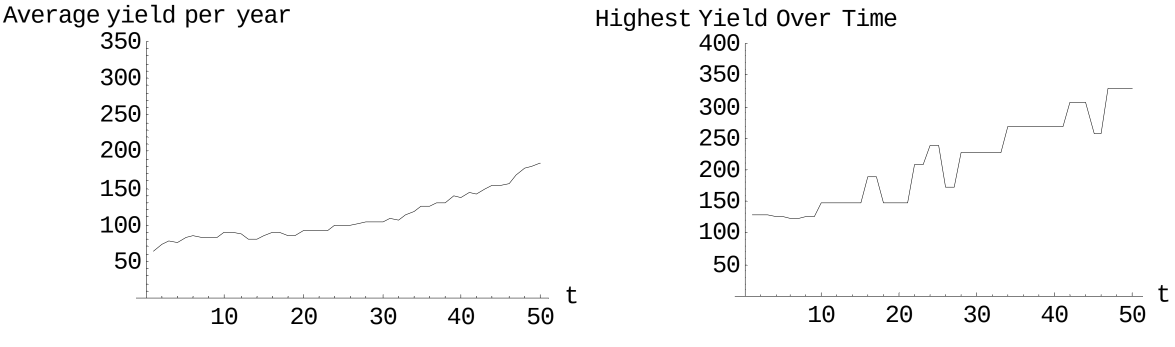

Fig. 2 Average yields and highest yield over time with pest infestation (pestRed = 0.1)

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[11] As reported above, 1/3rd of worldwide yields are lost annually to insects, diseases and weeds (Saedler 1995).

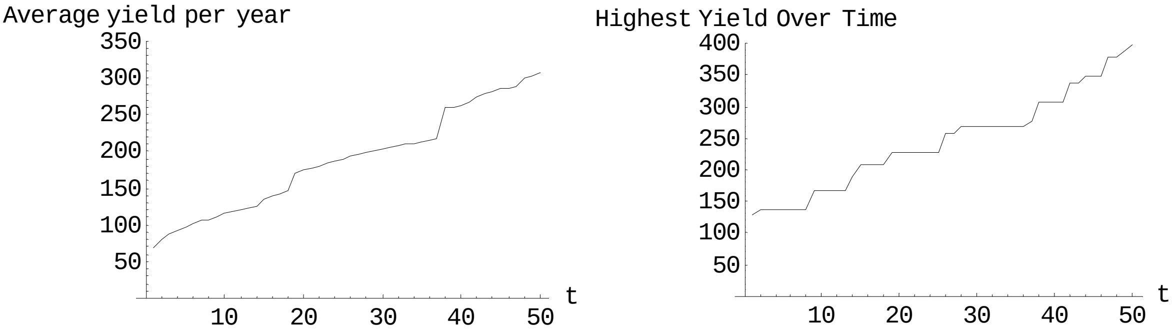

Fig. 3 Average yields and highest yield over time without pest infestation (pestRed = 0)

The rate of environmental adaptation also has an influence on the choice of the best strategy. Whereas Random Search is a profitable strategy for low or no pest infestation rates, it becomes substituted by the mixture of imitation (imiProb 0.5) and recombinant search for realistically high rates of pest infestation (Fig 4). This is an interesting finding, because new HYVs that are quickly adopted by imitating agents are more likely to be infested by newly adapting pest. On the other hand, however, it is particularly this quality that enhances the need to move on, because the agents can not “lie back” on a once discovered best seed. A high rate of adaptive destruction increases the speed with which better solutions have to be found and Random Search is not quick enough for this task.

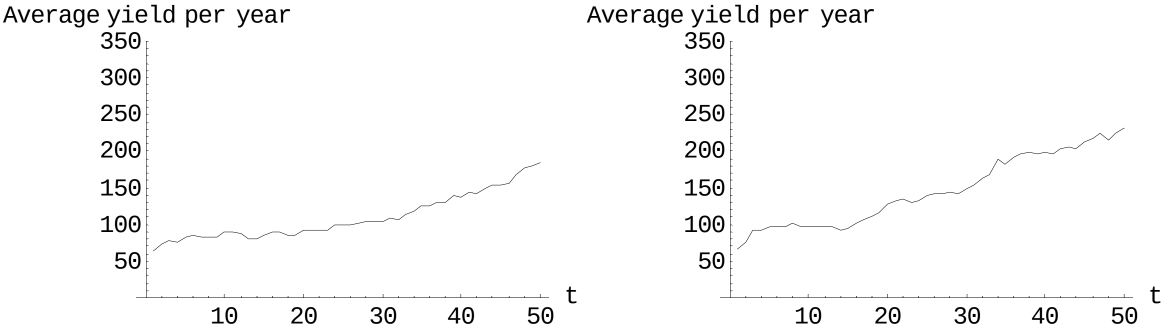

Fig. 4 Average yields over time with high pest infestation (pestRed = 1) for Random Search (left) and Imitation with recombinant search (right)

The importance of seed diversity

The paper intended to show to what extend seed variety is necessary for long term adaptability of the agricultural sector. A first effect to notice is that even for a zero rate of plain imitation – i.e. adoption of YHV – the number of varieties goes down considerably with time from about 40 in the beginning to an average of 5 after 50 time steps (Fig. 5). Some initial varieties provide very low yields, pests reduce yields and agents are inclined to look for something better, even if not allowed to buy the current HYV right away. This reduction affects possible individual and particularly summed up yields of the whole sector and results in the worst performance of all strategies over different settings.

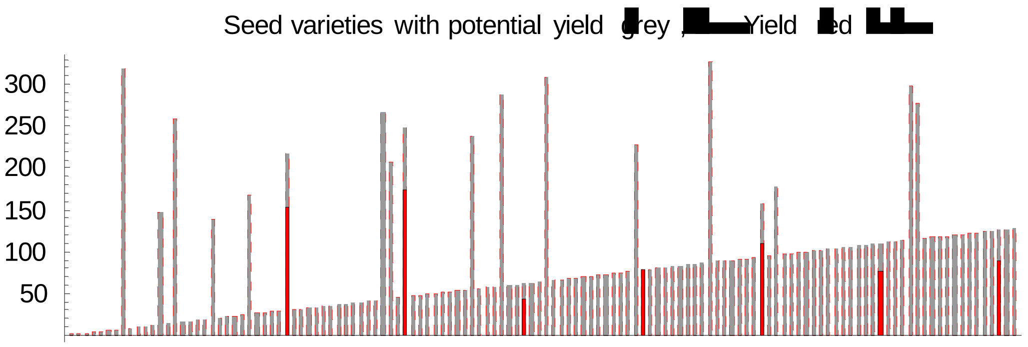

Fig. 5 Fitness base and actual yields at time 50 (crossProb =.75, evol/randProb= 0.0014, imiProb = 0, pestRed = 0.1)

Allowing for a higher rate of Random Search, does enhance on-farm diversity to an average of 10 remaining varieties at the end. And it corresponds to a larger gene pool, available for tests and seed breeding. This setting therefore provides higher yields, as can be seen, when comparing (Fig. 5 and 6), as well as the results in the corresponding columns in Table 1.

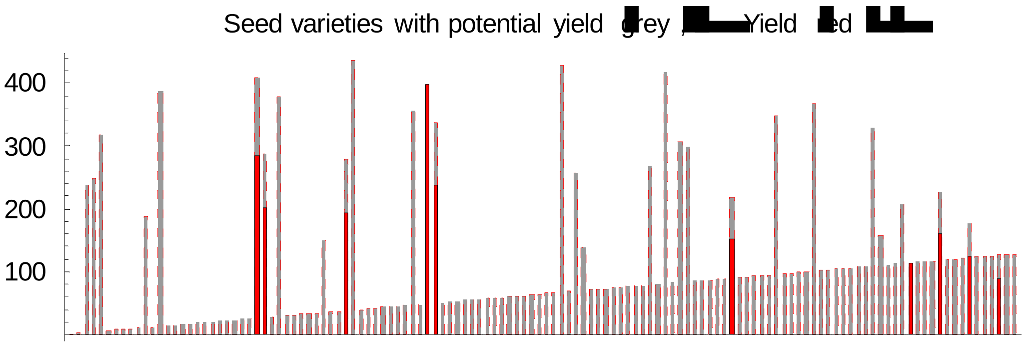

Fig. 6 Fitness base and actual yields at time 50 (crossProb =.75, evol/randProb= 0.014, imiProb = 0, pestRed = 0.1)

The highest seed diversity is maintained, if a lot of variations can be tested. On-farm diversity can remain at a level of 20 (Fig. 7) and yields are higher than for any other strategy.[12]

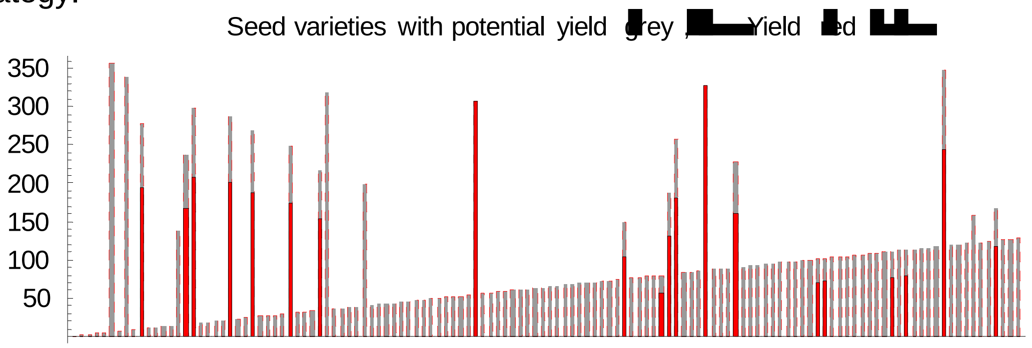

Fig. 7 Fitness base and actual yields at time 50 (crossProb =.75, evol/randProb= 0.14, imiProb = 0, pestRed = 0.1)

However there seems to be a problem for the maintenance of seed variety, even besides the “natural” unifying tendency, present in all settings. For a realistically high level of pest infestation, the abandoning of Random search in favour of a highly

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[12] The higher yields are not visible from these figures but can be looked up in table 1.

imitative strategy (Imitation with Recombinant Search, Imi 0.5) is more profitable. This however, leads to a reduction of diversity (Fig. 8). As there still is a considerable level of recombinant search (half of the seed choices are not based on imitation), the remaining gene pool of about 10 varieties seems to suffice for further enhancements. As already commented on in the above subsection, a high rate of adaptive destruction increases the speed with which better solutions have to be found. Random Search is not quick enough for this task and has to be abandoned for a certain level of imitation if yields are to be kept high. Imitation works better, although seed variety is reduced. The problem with this result is that it’s actually what seems to happen in the agricultural sector. If they have access to higher yielding seed and the means to buy it, farmers are inclined to adopt well performing varieties – even if it’s not always the current best HYV. And they do reduce diversity thereby.

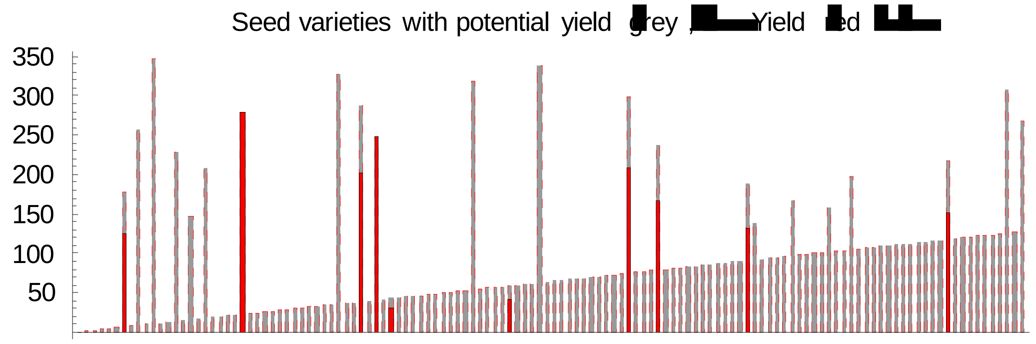

Fig. 8 Fitness base and actual yields at time 50 (crossProb =.75, evol/randProb= 0.0014, imiProb = 0.5, pestRed = 0.1)

However, an additional enhancement of diversity loss is critical for further development, as a comparison between the strategies of pure imitation (imiProb = 1) (with only a natural level of evolution) and imitation with recombinant search (imiProb = 0.5) reveals. Although profitable for individual agents in a short term perspective, the agricultural sector as a whole becomes to homogenous by high rates of imitation. This effect also becomes quickly visible in a stagnation of the whole population (Fig. 9). After being initially profitable to adopt new HYVs quickly, the uniformity of the remaining seeds undermines every further development, even for a remaining level of hypothetical crossbreeding. It doesn’t help much, if there’s nothing more to breed on. Imitation takes variety needed for further inventions out of the gene pool. Higher short term and individual yields do not compensate diminished breeding chances. The example in figure 6 shows the fallacies of a too eager imitation at an early stage. The formerly 50 seed varieties have been reduced to only 3, concentrated on varieties that have been HYVs a long time ago. The opportunities to discover significantly more profitable seeds are foregone.

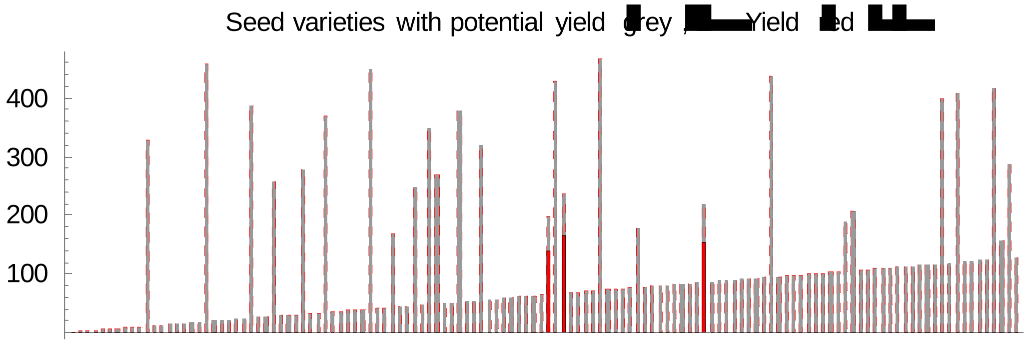

Fig. 9 Fitness base and actual yields at time 50 (crossProb =.75, evol/randProb= 0.0014, imiProb = 0.5, pestRed = 0.1)

But everything else being equal (low random influences at the level of natural evolution evol/randProb= 0.0014), a high rate of imitation (imiProb = 1) is better for overall yield than no imitation at all. It is interesting to note that this is inversely for individual highest yields. That effect becomes visible in the individually best yields in Table 1, which are lower if seed diversity decreased due to rising uniformity. At first sight, this seems counterintuitive, but there is a reason. For the whole agriculture, the faster rising yields compensate for the diminished opportunities to develop new HYVs, because most agents would not have used HYVs anyway in a less imitative setting. In a summed up perspective, it´s better if everybody gets the opportunity to improve – even if not to a really high level – than if real HYVs can be developed on the basis of larger diversity, but can only be used by a low percentage of all agents. However, as stated above, the socially best imitation rate is still not the highest but a moderate one.

6 Conclusions

Genetic diversity is the main source of agricultural productivity rises, because new seed varieties are developed on the basis of existing seeds. Mostly attributed to improved crop seeds, yields are estimated to have multiplied at least by 3.5 over 45 years. Some sources even give considerably higher values. At the same time, the necessary gene diversity diminishes considerably, precisely because of the widespread adoption of high yielding varieties (HYVs). Thus the same phenomenon generating remarkable success is undermining its continuation. This is all the more alarming, as the seeds in use are infested by quickly adapting pests and diseases in 3 to 7 years after their launch. Further breeding of new seeds is crucial to adapt in turn to these new threads. A diverse gene pool is needed for this task.

An artificial conservation of germplasm in gene banks is no real alternative to on-farm conservation. Keeping the seeds intact and replanting them regularly to maintain their fertility is difficult and costly and the seed may still be useless after not having participated in natural evolution for a long time. Therefore, the enormous loss of on-farm diversity is disturbing.

The paper tried to investigate, to what extend seed diversity is needed for continuing advances and what strategies of the farmers are most profitable for different rates of environmental change – i.e. the appearance of new pests. It did so, by using a Multi-Agent model with an environmental level, representing the potential productivities of different seed varieties and an agent level, containing 50 farmer agents. 5 different strategies for these agents, ranging from pure random search over crossbreeding to pure imitation, were investigated in their effect on yields. Different parameter settings, corresponding to different environmental conditions and agents strategies, have been tested in their influence on the yield performance of the whole agricultural sector over the observed time span and on the development of the highest yielding variety over time. Each individual run goes over 50 time steps.

The influence of different rates of environmental change

The speed with which crop seeds can be infested by pests, reducing the infested crop yield by 30%, has been varied from no pest infestation to a realistically high pest infestation. The probability is rising with the number of farmers, adopting a particular seed. In the summed up yields over all agents and all runs (i.e. the outcome of the agricultural sector over the whole observation time) the difference between no and a realistically high pest reduction rate is considerable and reaches the 30% known from literature for worldwide yield losses.

The rate of pest infection also has an influence on the performance of different search strategies. Whereas Random Search is a profitable strategy for low or no pest infestation, it becomes substituted by a mixture of imitation and recombinant search for realistically high rates of pest infestation. Although a faster adoption of new HYVs even enhances their risk to be infested themselves. But the faster rate of devaluation of once profitable seeds enhances the speed with which a switch to better solutions deems necessary. Random Search is not quick enough for this task.

The importance of seed diversity

The paper intended to show to what extend seed variety is necessary for long term adaptability of the agricultural sector. A first noticeable effect is that diversity diminishes more or less importantly under all circumstances. When we only consider natural evolution and crossbreeding – i.e. no adoption of HYVs and no trial and error search – the losses are highest, which results in the worst overall performance of all scenarios. Allowing for a moderate rate of random search, does enhance on-farm diversity. It corresponds to a larger gene pool, available for tests and seed breeding. But the highest seed diversity is maintained, if a lot of variations can be tested and yields are higher than for any other strategy. So long term agricultural performance is clearly related to seed diversity.

However, there seems to be a problem for the maintenance of seed variety, even besides the “natural” unifying tendency, present in all settings. For a realistically high level of pest infestation, the abandoning of random search in favour of a highly imitative strategy becomes more profitable. But it leads to a reduction of diversity. As there still is a considerable level of recombinant search (half of the seed choices are not based on imitation in this strategy), the remaining gene pool seems to suffice for further enhancements. As stated above, a high rate of pest infestation increases the speed with which better solutions not only have to be found, but adopted as well. What is disturbing about this result is the fact that it seems to map the current practice of the agricultural sector. Obviously, farmers are inclined to adopt well performing varieties, if they have access to and the means to buy them. Although reducing diversity thereby, it is still most profitable for the whole sector. Only an additional enhancement of diversity loss is critical for further development, which rules out the strategy of pure imitation. Although profitable for individual agents in a short term perspective, the agricultural sector as a whole stagnates quickly at a low level.

Nevertheless, for a low level of random search, pure imitation is still better for overall yields than no imitation at all. At first sight, this seems counterintuitive, but the explanation is straightforward. For the whole agricultural sector, the faster rising yields compensate for the diminished opportunities to develop new HYVs, because most agents would not have had access to HYVs anyway in a setting without the opportunity to imitate. In the general perspective it’s better if everybody improves a bit, than if HYVs can be developed on the basis of larger diversity, but can only be used by a low percentage of all agents.

Unfortunately we can not conclude by stating that farmers were simply behaving irrational in their current behaviour and that another collective strategy would benefit them all. Although the model showed that diversity is important for further development, the best performing strategy under realistic environmental conditions reduced variety. The model results couldn’t prove that maintenance of high levels of on-farm seed varieties would benefit the agricultural sector in the long run. Under the current level of pest infestation, foregone yield enhancements, caused by sticking to low yielding varieties, were higher than later gains due to facilitated breeding. If society still wants to preserve a high level of diversity, it has to recur to other options. Bardsley (2003) investigated possibilities to secure crop diversity by supporting on-farm conservation of agrobiodiversity in marginal productive regions in Switzerland, Turkey and Nepal. Such regions, with specific local conditions, are particularly suited for such attempts, because they are the most likely to refrain from scientifically bred varieties anyway, the latter often being badly adapted to their particular needs. But variety risks to disappear even in remote areas, due to – for these regions mostly empty – promises of global industries, trying to sell their high-performance seeds worldwide. Bardsley discuss the necessity and possibility to actively sustain these last niches. A possible solution was proposed by Hampicke (1999), who suggested paying farmers not only for their produce but for their role in ecosystem maintenance.

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