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RESOLVING THE 10,000 - YEAR CONFLICT BETWEEN AGRICULTURE AND NATURE

RJEŠENJE 10 000 GODIŠNJEG NESPORAZUMA IZMEĐU POLJOPRIVREDE I PRIRODE

T. S. Cox

ABSTRACT

Agriculture's impact on the Earth has been worsened by industrial farming, but the fundamental problem goes back 10,000 years to the domestication of those annual crops that are still the staples of our food supply. When we think of how many civilizations built on annual cropping have fallen not to the sword but to the plow and of the soil and water degradation that continues to haunt agriculture, we can only lament the fact that the domesticators didn't focus more on erosion-resistant perennial species. Three-fourths of the world's food-producing land is, and will continue to be sown to grains, legumes, and oilseeds. Annual crop species, with their ephemeral, usually shallow root systems, are incapable of fostering a thriving soil microflora or micro-managing nutrients and water in the way communities of perennial plants do.

The means that modern agriculture relies upon to overcome the weaknesses of annual crops cannot simultaneously resolve all of the key problems. No-till methods curtail erosion in the top layer of soil but, done consistently on a large scale, they require unacceptable levels of chemical inputs and leave the lower soil profile unimproved. Organic methods eliminate toxic chemicals but not the equally harmful effects of tillage or the soil erosion and water deterioration that occur as consequences. In an effort to resolve the dilemma, a small number of plant breeders in the US, Australia, and other countries are now breeding perennial counterparts of annual grain and legume crops. The difference in seed production between annuals and perennials is a result of contrasting selection pressures during the two groups' evolutionary histories. Selection pressure

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applied in yet a different direction by plant breeders can increase seed yield and produce perennial grain crops. When it is done, the 'hardware' represented by perennial grains, combined with the 'software' of organic methods, can finally end the conflict between food production and ecological health.

Key words: crop domestication, perennial crops, soil erosion, no-till system, organic agriculture

SAŽETAK

Industrijski pristup znatno je uvećao negativni utjecaj poljoprivrede na svijet, no problem je mnogo stariji. Pred 10 tisuća godina započeta je domestikacija jednogodišnjih usjeva koji su i danas osnova prehrane stanovništva. Kad razmišljamo koliko je civilizacija, koje su se temeljile na jednogodišnjim usjevima palo, ne od mača, već od pluga i njime prouzročene degradacije tla i voda, možemo jedino požaliti što naši preci nisu posvetili više pažnje domestikaciji višegodišnjih usjeva koji sprečavaju eroziju tla. Tri četvrtine poljoprivrednih površina zasijano je žitaricama, mahunarkama i uljaricama. Plitak korijen ovih jednogodišnjih usjeva nije u stanju održavati razvoj mikroflore, niti koristiti mikrohranjiva i vodu tako uspješno kako to rade višegodišnji usjevi.

Načini izbjegavanja ovih slabosti jednogodišnjih usjeva ne rješavaju problem u potpunosti. No-til tehnologija sprečava samo površinsku eroziju, no primijenjena na većim površinama i kroz dulje vrijeme zahtijeva neprihvatljivo visoke doze kemikalija i ne poboljšava dublje slojeve tla. Ekološki pristup izbjegava toksične kemikalije ali ne rješava negativni učinak oranja (eroziju tla). U nastojanju rješavanja ovog problema mali broj američkih i australskih oplemenjivača započeo je stvaranje višegodišnjih žitarica i mahunarki. Razlika u proizvodnji sjemena između jednogodišnjih i višegodišnjih usjeva je rezultat selekcijskog pritiska tijekom evolucije. Danas, selekcijski pritisak usmjeren na drugi način može kao rezultat imati višegodišnji usjev s povećanim urodom zrna. Kada to bude postignuto 'hardver' višegodišnjih usjeva i 'softver' ekološke metode uzgoja mogli bi konačno prekinuti nesporazum između proizvodnje hrane i degradacije tla odnosno ekološkog zdravlja okoliša.

Ključne riječi: domestikacija usjeva, trajni usjevi, erozija tla, no-til metoda, ekološki uzgoj.

INTRODUCTION

Humans now directly manage 27 percent of the Earth's surface area, harvesting more than 40 percent of the planet's biological productivity for our own uses. Yet food production per person is on the decline, and agriculture worldwide is doing more than ever to worsen the global ecological crisis. Like the Hindu god Shiva, today's agriculture is both a creator and a destroyer. Its dual nature results in part from the conscious decisions of farmers, agribusiness executives, government officials, and food buyers. But it is also inherent in the crops and cropping methods that humans have relied upon for 10,000 years.

THE PROBLEM OF AGRICULTURE

Since its very first days, agriculture has rested on a foundation of annual plants that are grown from seed every year and harvested for their seed. That requires tilling of the soil. Tillage can be done on a small scale – in small, intensively hand-managed plots or on annually flooded land along a river -- without causing great harm. But every civilization that has practiced tillage on a large scale has suffered the often catastrophic consequences of soil erosion (Lowdermilk, 1953; Hillel, 1991). Industrialization has compounded the problem through fossil-fuel burning and chemical contamination.

The world's natural landscapes are covered mostly by perennial plants growing in mixed stands (Chiras et al. 2004), whereas more than two-thirds of global cropland is sown to monocultures of annual crops. Conversion from natural to agricultural landscapes dramatically alters ecological conditions. Across the planet, more land has been converted from perennial to annual cover since 1950 than in the previous 150 years. This recent expansion of cropland has made it more and more necessary to apply chemical fertilizers and pesticides, which disrupt natural nutrient cycles and erode biodiversity (Tilman et al. 2001, Cassman and Wood 2005).

Perennial plants are highly efficient and responsive micromanagers of soil, nutrients, and water. Annual crops are not; they require churning of the soil, precisely timed inputs and management, and favorable weather at just the right time. With shorter growing seasons and ephemeral, often small root systems, annual crops provide less protection against soil erosion, waste water and nutrients, store less carbon below ground, and are less tolerant of pests than are perennial plant communities (Glover et al., 2007).

Today, vast swaths of entire continents have been scoured of their perennial vegetation, leaving the soil uncovered for a good part of the year. Even when the soil is covered during the growing season and even under organic management, lightly rooted annual crops fail to manage water and nutrients the way their deeply- and densely-rooted, persistent perennial antecedents did. Agriculture's destruction of perennial root systems has wrecked entire underground ecosystems, subtracting from the soil much of what makes it soil.

It is a problem older than history. Agriculture has always depended largely on annual grass and legume species that were domesticated by humans between 5000 and 10,000 years ago. That domestication of annuals set in motion a somewhat ironic series of events. First, annual grain crops made civilization both possible and necessary. Much later, civilization -- largely through exploitation of fossil fuels and synthetic chemicals -- created conditions under which agriculture could become both extraordinarily productive and ecologically destructive. But today, it is the fruits of the very civilization made possible by agriculture – scientific knowledge, data, and techniques -- that have clearly revealed to us both the necessity and the possibility of correcting the well-intentioned wrong turn our species made 10,000 years ago (Jackson, 1980).

NO-TILL, ORGANIC, AND PERENNIAL

By far the most important factor that determines the degree of soil erosion in a field is the type of vegetation – annual or perennial – that covers the land. In one field experiment encompassing 100 years of data collection, perennial crops were more than 50 times more effective than annual crops in maintaining topsoil (Gantzer et al. 1990). So-called "no-till" methods (in which annual crops are farmed without tillage) reduce soil loss but require heavy chemical inputs. No-till also performs as poorly as conventional farming in controlling percolation of nutrients and water out of the soil profile. (Randall and Mulla 2001).

Global data for maize, rice, and wheat indicate that only 18 to 49 percent of nitrogen applied as fertilizer is taken up by crops; the remainder is lost to runoff, leaching, or volatilization (Cassman et al. 2002). That occurs with or without tillage. Nitrogen losses from annual crops may be 30 to 50 times higher than those from perennial crops (Randall and Mulla 2001). Organic farming with annual crops solves the problem of chemical contamination but, except in rare circumstances, requires as much or more tillage than conventional agriculture. And the inadequate root systems of annual species handle water and nutrients inefficiently even when crops are grown organically.

Modern societies, stuck as we are with annual crops, have little alternative but to treat grain cropping not as a source of life but as a dangerous activity against which humans and nature must be protected. Environmentally conscious researchers and farmers are making the most of the only perennial plants available to them, by growing more hay and pasture; growing perennial biofuel crops; planting more trees and grass along rivers and streams to soak up the contaminants that hemorrhage from cropland; and taking more erodable lands out of grain production altogether (Jordan et al., 2007). It's a monumental and discouraging task made necessary because we are still dependent on annual crop plants.

We cannot go back to the crossroads where our ancestors took that wrong turn, and a return to ancient farming methods would not address the problem of annual cropping. But by taking the successes of organic farming through another stage of evolution, it may be possible to produce food while simultaneously allowing the Earth itself to manage the soil, water, and air as it did before the dawn of agriculture.

To do that, we need perennial grain crops. Humans obtain three-fourths of our total calories from grains and oilseeds. By developing perennial grains, plant breeders could help dramatically enlarge that portion of the agricultural landscape that is kept intact by diverse, dense root systems. With a few very small-scale exceptions, no perennial cereal, pulse, or oilseed crops currently exist. But through a massive, long-term plant breeding effort, that situation can be resolved (Cox et al., 2002, 2006).

THE MISSING LINK IN CROP DOMESTICATION

Neolithic people gathered and ate foods from a huge range of plant species, but once they began domesticating, it was annual plants like wheat, barley and rice that they transformed. Among the world's top 20 staple food crops, the banana is the lone non-woody perennial. Perennial grain species are not to be found anywhere among the world's crop plants (Cox et al., 2006).

Ancient grain-gatherers apparently did eat the seed of some perennials. Anthropologists have observed traditional methods of harvesting seed from perennial grasses in Poland, Mongolia and North America (Bohrer, 1972). People living south of the Sahara harvested the seed of a wide range of perennial grasses (Harlan, 1989). The Vikings probably cultivated perennial lymegrass before barley reached Scandinavia (Griffin and Rowlett, 1981). Archaeologists have found charred seeds of three perennial and twelve annual species of small-grained grasses that people were consuming 23,000 years ago at a site in what is now Israel (Weiss et al., 2004). Yet no domesticated perennial grain species were handed down to us by plant domesticators.

Perennials were unlikely to follow Neolithic people back to the fertile, churned soil around their dwellings in the way annual plants did. In any such situation, they would have been overwhelmed by the weedy annuals that specialize in colonizing such unfriendly territory by growing quickly and scattering their seed before dying. Meanwhile, in undisturbed natural stands, perennial plants re-growing from well-established roots and rhizomes would have been much more vigorous than new seedlings of the same species emerging from dropped seeds. People would have felt little incentive to sow a new generation of perennials as long as plants returned from previous seasons continued to produce well.

Changes in plant traits during domestication and breeding of annual crops occur through cycles of sexual hybridization and selection. With annuals, the mechanics of food production and plant breeding are virtually identical. Through that process, Neolithic people domesticated annual plants without, at least initially, even realizing that they were doing so (Hillman and Davies, 1990). But collectors of perennial seeds, harvesting year after year from the same perennial plants with no incentive to re-sow, would have had little or no genetic effect on the population.

Woody perennials became a part of the human diet, but herbaceous perennials were left behind. But today, a small number of plant breeders are beginning to domesticate perennial species and hybridize them with annual relatives, in an effort to open the door to the kinds of dramatic changes in seed production and other traits that plant breeders have achieved in annuals.

The high yields of modern crops are the result of long-term, intense selection for improved harvest index (allocation of biomass to seed rather than vegetation) and decreased intraspecific competition. On the other hand, as argued by DeHaan et al. (2005), the relatively low seed yields of wild perennial species result from natural selection in highly competitive environments. The evolutionary fitness of a wild annual plant is heavily dependent on seed production and dispersal, but the fitness of a wild perennial depends more on the survival of vegetative structures than on seed traits. Therefore, it’s not surprising that many (but not all) wild perennials have low seed production.

DeHaan et al. (2005) predicted that artificial selection in a properly managed agricultural environment could increase seed yield while maintaining perenniality. Artificial selection has the potential to generate perennial grain crops with acceptable yields, if it is applied to agronomic traits and perennial growth habit simultaneously. This is suggested by four characteristics of perennial plants that differentiate them from annual plants and provide them with extra resources that can be re-allocated to grain production (Cox et al., 2006):

- Better access to resources and a longer growing season,
- More conservative use of nutrients,
- Generally higher biomass production both above- and below-ground, and
- Sustainable production on marginal lands

CURRENT PERENNIAL-GRAIN RESEARCH

Through our research at The Land Institute, we have concluded that, unlike a field of maize or soybean, a field of perennial grain-bearing crops can provide food while at the same time protecting soils, water, and biodiversity. The genetic raw material is available, ready to be put to use. The Land Institute and a few universities and other agencies have created the foundations of breeding programs that will, given decades of work, develop a wide array of perennial grain crops. Most current genetic and breeding effort is going into the following species and species hybrids:

Intermediate wheatgrass (*Thinopyrum intermedium*) is a perennial relative of wheat (*Triticum aestivum*). We are domesticating this species by breeding for increased seed size, seed yield, and ability to thresh freely. The main approach is to evaluate thousands of individual plants over two years, followed by a third year to intermate the 5 percent of best-performing plants. We have completed one cycle and are now in a second. Experiments have shown that the first round of selection increased mean yield by about 18% and mean seed size by about 10%. Some individual families are much larger. In a separate population, four fast cycles have increased the fraction of free-threshing seed from about 8% to around 30%.

Wheat and **triticale** (X *triticosecale*) can be hybridized with several different perennial species. We have crossed these annual species with perennial relatives, primarily intermediate wheatgrass, and backcrossed to the annual to produce thousands of relatively fertile, large-seeded plants. In the greenhouse, a large proportion of these plants continue to live after their mature seed has been harvested, but in the field we have so far only identified about 10 plants out of thousands that were able to re-grow after harvest.

Figure 1. Left: A conventional, tall forage-type intermediate wheatgrass plant. Right: A stiff-strawed, dwarf intermediate wheatgrass plant from a second cycle of selection for grain production. Plants of the latter type have increased to approximately one percent frequency in the population. Both plants photographed in their second year of growth.

To obtain larger numbers of perennial plants, we have crossed hundreds of interspecific hybrid plants to the perennial parent, wheatgrass. We produced hundreds of hybrids, but many of them were sterile, as expected. We have since crossed the few plants that produced viable pollen with pollen-sterile plants in an effort to restore fertility. A few resulting plants have exhibited good fertility, large seed, and vigorous regrowth.

Grain sorghum, a drought-hardy feed grain in the US and a staple food in the Eastern Hemisphere, can be hybridized with the tetraploid perennial species *Sorghum halepense*. We have produced large plant populations from hundreds of such diploid x tetraploid hybrids. The better strains currently produce about 40 percent of the grain yield of their annual grain sorghum parents, and their seed is about half the size of grain sorghum's – a fourfold improvement over *S. halepense* and some of the largest seed of any perennial grain-in-development.

Figure 2. Pollinating male-sterile grain sorghum plants, on left. Plants on right are the pollen source. They are perennial sorghum plants from the first cycle of crossing between S. Biocolor and S. halepense

A tropical plant, sorghum survives the winter in temperate regions through survival of rhizomes, or underground stems. Rhizome development is a complex genetic trait, dependent on 9 of sorghum's 10 chromosome pairs (Paterson et al., 1995). Winter survival is even more complex, and harder to achieve through breeding. However, we have found no strong negative correlations between these components of perenniality on the one hand and grain productivity on the other.

Illinois bundleflower (*Desmanthus illinoiensis*) is a native prairie legume that produces relatively large harvests of protein-rich seed (Kulakow, 1999). It is a strong candidate for domestication as a crop. The Land Institute has assembled a large collection of seed from a wide geographical area and initiated a breeding program. Making controlled hybrids is extremely difficult technically, but methods have been developed to foster natural hybridization and identify hybrids using morphological or molecular markers. Non-shattering families – crucial to domestication – have been selected and used as initial parents. The species is a strong, widely adapted perennial, and selection criteria will include shattering resistance, synchronous maturity, seed yield, and seed size and quality.

Maximilian sunflower (*H. maximiliani*) and **Kansas rosinseed** (*Silphium integrifolium*) are native perennials related to sunflower. The Land Institute is in the process of domesticating these species as perennial oilseed crops, via methods similar to that described above for intermediate wheatgrass. There is a parallel program for inbreeding to expose rare, valuable recessive genes. Phenotypic variation is extensive in these species. In addition to the usual traits, selection pressure is being applied to fuse the numerous small seed-heads into larger, more compact heads and eliminate seed dormancy. In the case of the large-seeded Kansas rosinseed, selection to increase seed fertility of the head is in progress.

Sunflower (*Helianthus annuus*), the highly productive annual oilseed crop, can be hybridized with several perennial species in its genus, including the diploid Maximilian sunflower and two hexaploids: rigid-leaf sunflower (*H. rigidus*) and Jerusalem artichoke (*H. tuberosus*). Hybrids between annual and Maximilian sunflower are highly sterile, unless their chromosome numbers are doubled to produce tetraploids. The best strategy to produce perennial, partially fertile plants is to cross both annual and Maximilian sunflower to the hexaploid species to produce tetraploid plants and then inter-cross the different tetraploids.

Large perennial populations have been produced in this way, and they are being subjected to selection for greater seed fertility. There are many more groups of species that could be used to develop perennial grains (Cox et al., 2002).

A NEW ORGANIC AGRICULTURE

The perennial grain crops listed above, and others, are intended to be grown in a food-producing system that replicates as closely as possible the ecological functioning of the natural landscape it replaces – in The Land Institute's case, the prairie grassland. In other regions, different sets of perennial crops can be used with similar effect, to be as hardy and resilient as a forest or a savannah, or whatever ecosystem preceded human habitation in a given region. What all such future systems have in common is that they will be based on perennial plant communities with ample genetic diversity both among and within species, and that the energy that supports them will be supplied by the sunlight that falls directly on them. They must function independently of fossil energy and synthetic chemicals. Researchers in organic and sustainable agriculture research have, out of necessity, attempted to mitigate the impact of agriculture by improving what I'll call the "software": the application of experience, knowledge, techniques, and natural materials to existing annual crop species. But those annual species represent a kind of dysfunctional "hardware" that limits what can be achieved with even the best agricultural "software." To open up possibilities for truly new agriculture that is sustainable in the long term, new hardware – a wide range of perennial grain crops - is needed.

Plant breeders have long had difficulty finding their role in organic and sustainable agriculture. Now we have a clear-cut, difficult, but achievable mission laid out for us: to develop perennial crops that can make agriculture truly sustainable for the first time ever (DeHaan et al., 2007). It will require a huge effort that must extend far beyond The Land Institute to agronomy, horticulture, and plant breeding departments in institutions across the globe. Plant breeders live in the future. Even in well-established crops, the pollinations we made this spring or summer won't lead to cultivars until we are well into the next decade. Breeding varieties and hybrids only for currently available farming systems becomes a self-fulfilling prophecy. Plant breeders in organic agriculture, indeed all plant breeders, must instead work toward goals that will be important in the longer term. And that "longer term" will by necessity include perennial grain crops.

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Adresa autora – Authors address:
Thomas Stanton Cox,
E-mail: t.s@cox.net
The Land Institute in Salina,
KS, USA.

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Thomas Stanton Cox is a senior scientist at The Land Institute in Salina, KS, USA. He received a Ph.D. in plant genetics from Iowa State University in 1983. He worked as a wheat geneticist for the US Department of Agriculture from 1984 to 1996, where he developed disease-resistant germplasm. His work at The Land Institute since 2000 is on breeding perennial grain crops, including perennial wheat, sorghum, and sunflower. He has published more than 90 articles in scientific journals and chapters in books. His book *Sick Planet: Corporate Food and Medicine* was published in March by Pluto Press (London). He contributed to another book published this year, *Edible Estates: Attack on the Front Lawn* (Metropolis Books). An earlier book, *Intellectual challenge of self-destruction technology* (Matica hrvatska, Krizevci, 2003) was written with cooautor Marijan Jost.

His environmental commentaries have appeared in newspapers across the US. He writes approximately monthly for the top tier of progressive web magazines: AlterNet, CounterPunch, and Common Dreams.