Nature's fields: a neglected model for increasing food production

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Natural ecosystems can offer attractive models for sustainable crop production, but hitherto only relatively complex vegetation has been considered. This review focuses on simple vegetation with a single dominant species. There are many reports of wild relatives of rice, sorghum and wheat in simple, extensive, often annual and apparently stable natural stands. These 'wild fields' could provide appropriate models for the ecologically sound management of cereal fields. The authors suggest that early farmers had a working knowledge of the ecology of wild cereal vegetation: this was important during cereal domestication and subsequently in crop management. There is a need for field research on monodominant wild cereal vegetation to confirm the value of simple natural models and to provide an ecological pedigree for the sustainable management of fields for food production.

Despite the success of the green revolution over the past three decades in increasing food production (and lowering food prices for the poor) there is a continual need for farming to produce more food as human populations rise. Global demand for cereals, our main food, is expected to increase by 35% from 1997 to 2020, to 2,497 million tons.[1] In the past, more land could always be converted to agriculture, but now the possibilities of expanding cultivated area are limited. In future, extra food will have to come from increasing crop yields. This means more, and more effective, inputs of labour, nutrients and knowledge, including, for example, what has been called the 'unending virtuosity' of traditional rice farmers in Indonesia, extracting yet more food from the same land.[2] Over the coming decades, the world must feed more people, but there is widespread concern over how this can be done. Will attempts to produce more food from the same land both undermine the sustainability of farming and damage the broader environment?

Natural agriculture

The 'Millennium Series' of the British Broadcasting Corporation's Reith Lectures tried to answer such questions by discussing sustainable development. In his overview of the series, Prince Charles argued that we must work 'with the grain of nature' and follow the 'genius of nature's designs, rigorously tested and refined over millions of years'.[3] While of increasing appeal to politicians dealing with consumers suspicious of food safety, is a 'natural design' approach to agriculture technically feasible?

It seems so. There is a strong foundation on which to build. The belief in natural models for agriculture is attractive, long-standing and pervasive. For example, Howard, from his experience in India, thought that cultivators followed 'Nature's method as seen in the primeval forest'.[4] Geertz described shifting cultivation in Indonesia as a miniaturized tropical forest that 'apes the generalized diversity of the jungle which it temporarily replaces'.[5] Dahlberg thought that the peasant farmer 'knows that the mimicking of natural systems can greatly aid him'.[6] Jackson and Piper presented general arguments for basing agroecosystems on natural models:

- the patterns and processes discernible in natural ecosystems still remain the most appropriate standard available to sustainable agriculture;
- there was a need to model agroecosystems on nature's standards;
- reliance on an ecological perspective, 'nature's wisdom', could benefit rural cultures and landscapes.[7]

Such is the power of the 'natural' analogy for cropping systems that generic prescriptions for crop production 'in Nature's image' have been suggested.[8] Gliessman suggested that mimicking nature would allow the strong ecological foundation on which agriculture originally developed to be found again, by making use of natural ecosystem processes and interactions.[9] Ewel wrote: 'Native ecosystems are time-proven survivors, and it is logical to learn from them and imitate their useful traits.'[10]

A bias towards structural complexity

Unfortunately there is a substantial bias in the choice of which natural models could be of value to farmers. The bias favours only the more structurally complex and perennial natural ecosystems as suitable models for fields.[11] This bias could limit the usefulness of the concept of mimics of nature. Part of the bias is historical: early views related agriculture to complex tropical forest models and only more recently have perennial grasslands been considered as models, and then only for perennial polycultures.[12] But part of the bias was reinforced in the past by ecological theory that claimed that complex systems were stable and self-regulating.[13] This claim has been challenged repeatedly, but with little impact on the persistence of the 'natural diversity' prescription for all agriculture.[14]

Indeed, in attempting to justify complex fields, it has been suggested that diversity seems to be an inherent characteristic of most natural ecosystems.[15] There is the belief that a natural model for farming should always reflect the diversity of nature, with many species co-existing in complex and stable ecosystems.[16] It has been argued that perhaps as a response to observations and knowledge of natural ecosystems, people mimicked these systems of multiple species with their plantings of crops with dissimilar growth habits, maturities and resource needs.[17]

Based on the belief that natural vegetation is complex — indeed, must be to persist[18] — there has been a continual emphasis on the need for diversity between crops. High levels of biodiversity and complexity are thought to be essential in farmers' fields. Promotion of complex cropping systems is now wide-ranging[19] and complexity is also being promoted for sustainable pest management in agroecosystems.[20]

This has given rise to the associated belief that simple cropping systems are unnatural and unsustainable: Dahlberg noted the 'inherent instability of such biologically simplified systems as monoculture agriculture'.[21] The claim has been made that: 'It is not nature's way to allow large expanses of land to be planted to a single crop'.[22] Further, Altieri claims that monoculture systems are ecologically unstable in that they 'provide optimal conditions for unhampered growth of weeds, insects, and diseases because many ecological niches are not filled by other organisms',[23] and that 'monocultures in order to function *must be* predominantly subsidized by chemical inputs' (authors' emphasis).[24] In the continued belief that simple cropping systems are unnatural, Altieri now argues for 'breaking the monoculture'.[25]

There are wider agricultural policy implications to this 'nature is always diverse' philosophy and the accompanying polyculture mindset for agriculture. The World Resources Institute claims the need for a paradigm shift in agricultural research to promote an ecosystem approach upholding biological complexity, with a move from an emphasis on uniformity and monocultures to an emphasis on conserving and enhancing diversity.[26] The CGIAR — an important engine of the green revolution — is coming under increasing pressure to adopt ecological approaches to agriculture based on diversity.[27] The allocation of funding for agriculture in developing countries is now influenced by this bias towards complexity. For example, a recent policy statement from the World Bank directly equated agriculturally sustainable development with 'increasing the productivity of complex (as opposed to monoculture) farming systems'.[28]

Correcting the bias

This essay will challenge the ecological rationale of the current 'diversity' paradigm — which claims to be modelled on nature — as a prescription for *all* agriculture. This challenge is necessary for three reasons. First, there are dangers for agriculture and our food security from an undue reliance on any *single* ecological approach — such as that of complex natural models — to the vast range of conditions under which fields are farmed. Second, attempts to justify the value of complex models — the polyculture paradigm — by appeals to ecological principles are now suspect, given the revision or reversal of concepts such as a '*turbulence in ecology*', the '*radical changes in fundamental paradigms*' and the '*bit of a muddle*' that are a feature of recent ecological debate.[29] Third, botanists and archaeologists working in regions of crop domestication have repeatedly noted that the ancestral wild relatives of crops are characteristically found in extensive stands, dominated by a single, often annual species, and seemingly highly stable.

If this challenge to the polyculture paradigm can be substantiated there is significant potential for developing better management of cereal monocultures. This would be based on the ecology of actual natural models, rather than the generic rejection of monocultures as unnatural and unsustainable, now the hallmark of a supposedly 'ecological' approach to farming.

Are there simple 'fields' in nature?

The narrative of Darwin's voyage on the research ship, *Beagle*, is a classic of biology.[30] The great range of plants and animals encountered in the field by Darwin over this 5-year period was crucial for his development as a naturalist and for his theory of evolution by natural selection. Yet nothing impressed Darwin more than what we now call the biodiversity of the great kelp beds of the southern ocean. He first used his taxonomic knowledge to describe the biological wonderland of animals found in the kelp:

> The number of living creatures of all Orders, whose existence intimately depends on the kelp, is wonderful. A great volume might be written, describing the inhabitants of one of these beds of sea-weed. . . . We find exquisitely delicate structures, some inhabited by simple hydra-like polypi, others by more organized kinds, and beautifully compound Ascideae. On the leaves, also, various patelliform shells, Trochi, uncovered molluscs and some bivalves are attached. Innumerable crustacea frequent every part of the plant. On shaking the great entangled roots, a pile of small fish, shells, cuttle-fish, crabs of all orders, sea-eggs, star-fish, beautiful Holothuriae, Planariae, and crawling nereidous animals of a multitude of forms, all fall out together.

Darwin then applied the ecological concept of food chains to explain the importance of kelp beds: 'Amidst the leaves of this plant numerous species of fish live, which nowhere else could find food or shelter; with their destruction the many cormorants and other fishing birds, the otters, seals, and porpoises, would soon perish also'. Next, a century and a half before the concept of 'biodiversity hot-spots' came to be used by conservation biologists, Darwin underlined the biological richness of the kelp beds in a comparison with tropical forest, and found in favour of the kelp: 'Yet if in any country a forest was destroyed, I do not believe that nearly so many species of animals would perish as would here, from the destruction of the kelp.'

Why are Darwin's observations important for agriculture? Kelp (*Macrocystis pyrifera*) is a good example of a 'natural monoculture', an ecosystem dominated by a single plant species, found along rocky coastlines for thousands of kilometres in the Pacific and seemingly highly stable and productive. Moreover, Darwin's observation shows that in nature a single dominant species such as kelp can be vital to the survival of a vast diversity of animals feeding on and around the dominant species. Are there examples of natural monocultures more relevant to crop production? If so, what are the ecological determinants of these natural monocultures? Finally, can features of the ecology of natural monocultures be applied to increase the sustainability of farming?

It has now been recognized by ecologists that simple, monodominant vegetation exists throughout nature in a wide variety of circumstances. Indeed, Federoff and Cohen (reporting Janzen) use the term 'natural monocultures' in analogy with crops.[31] Monodominant stands may be extensive. As one example of many, Harlan recorded that for the blue grama grass (*Bouteloua gracilis*): 'stands are often continuous and cover many thousands of square kilometres' of the high plains of central USA.[32] It is of the utmost importance for the sustainability of agriculture to determine how these extensive, monodominant and natural grassland communities persist when we might expect their collapse.

Examples relevant to agriculture

The identification of simple natural models would be of greater and more direct value for agriculture if we could demonstrate that wild relatives of cereals grow in simple and stable natural stands. Reports of wild relatives of rice, sorghum and wheat seem to confirm that this is so.

Rice

If there is a natural model for monocrop wet-rice production it should be found in a region of domestication of rice, in South-eastern Asia, among wild relatives of domesticated Asian rice. Swamps and seasonally flooded rivers are the places to look. It has been suggested that single dominants are able to monopolize a swampy site to the virtual exclusion of any rival and any understorey.[33] There are multiple examples of this in the British flora, many of grasses.[34] In addition, swamp vegetation has relatively high productivity, generally around 1,500 to 2,000 g m^{-2} yr^{-1}. This is attributed to a plentiful supply of nutrients, due to flushing with nutrient-rich water, and low water stress for most of the year.[35]

The seasonally flooded rivers and deltas of the great silt-laden rivers draining the Himalayas seem to provide suitable ecological conditions for monodominant stands of wild rice. Almost a century ago Prain described the ecology of the wild rice relative, *Oryza coarctata*.[36] It was the most common and most plentiful grass species in the Sundarabans mangrove swamps of Bengal and:

> the first species to establish itself on the compensation banks of alluvium that are formed on the opposite bank of a river whenever the 'set' of the current produced erosion. Such banks vary in size from a few square yards to several acres; whenever they occur they are closely and uniformly covered by a sheet of *Oryza coarctata*.

These conditions are both marginal and seasonally disturbed by flooding.

There was a quite separate domestication of rice in Africa. Harlan described and illustrated harvests from dense stands of wild rice in Africa (*Oryza barthii*, progenitor of the African cultivated rice, *Oryza glaberrima*).[37] *Oryza barthii* was harvested wild on a massive scale and was a local staple across Africa from the southern Sudan to the Atlantic. Evans reported that the grain yields of wild rice stands in Africa and Asia could exceed 0.6 tonnes per hectare — an indication of the stand density of wild rice.[38]

The transition from monodominant stands of wild rice to rice monocultures seems to have been an outstanding success. The single most important cropping system in the developing world — wet rice in South and South-east Asia, is a sustainable monoculture. 'The stability of soil productivity under wetland rice farming has made rice production from the wetlands the world's most sustainable and productive farming system. It has been sustained on the same land for millennia.'[39] Bray described monocultural rice fields of the Lower Yangzi that 'clothe a smooth plain stretching as far as the eye can see'.[40] Such rice landscapes produce the staple food of one-third of the population of the world. As described by Bray, such rice monoculture is readily incorporated into complex farming systems with combinations of rice fields, fishponds and mulberry plantations to feed silkworms, and supports farm-based industries of cotton weaving and preparing sugar and tea for export. Bray noted that traditional rice monoculture was intensified in China with external inputs of lime, manure, silt and food residues. As a result of intensification, modern rice monocultures can support up to 1,497 persons per km² (a case study in Nguyen Xa, Vietnam).[41]

Sorghum

One of the best known examples of a widespread dominant grass is *Imperata cylindrica* in South-east Asia. Geertz commented on the '*notorious imperata savannah grass which has turned so much of Southeast Asia into a green desert*'.[42] Merrill noted that *Imperata* was persistent, dominant, and occupied vast areas.[43] It is the most dramatic example of monodominant grassland savanna. Savanna grasslands worldwide are often dominated by limited numbers of species, often from the grass tribe, *Andropogoneae*, a tribe which includes the genus *Imperata*, but also *Sorghum* and *Saccharum*, from which the crops sorghum and sugar cane were domesticated.

Sorghum itself can be found in monodominant stands. Harlan identified the *verticilliflorum* race of *Sorghum bicolor* as the progenitor of cultivated sorghums, and noted that it was found as the chief dominant, in enormous quantities, of the extensive tall-grass savanna of Sudan and Chad.[44] Harlan also noted for Africa: 'Massive stands of truly wild races of sorghum can be found widely distributed over the savanna zones'.[45] Sorghum was domesticated somewhere along a belt south of the Sahara from Chad to western Ethiopia.[46] The races, *aethiopicum* and *verticilliflorum* of *Sorghum bicolor* are often dominant grasses in the northern savanna of Africa.[47] These 'massive stands' of annual wild sorghum provide both an evolutionary and ecological pedigree for monoculture sorghum cropping.

So too for pearl millet (*Pennisetum australis*): massive monodominant stands of a wild relative, *Pennisetum purpureum*, are common in Africa. An example was clearly illustrated for the Sudan by Ferguson.[48] These wild fields could provide a simple, natural model for pearl millet cropping.

Wheat

Perhaps the strongest evidence of the importance of natural, simple models for cereal agriculture comes from immediate wild relatives of wheat. These are found in the Near Eastern region of domestication, where there has been the most intensive research on crop relatives. Botanists and plant collectors have repeatedly and emphatically noted the existence of dense stands of wild relatives of wheat. For example, in the Near East, Harlan noted that 'massive stands of wild wheats cover many square kilometers.'[49] Hillman reported that wild einkorn (*Triticum monococcum* subsp. *boeoticum*) in particular tends to form dense stands, and when harvested its yields per square metre often match those of cultivated wheats under traditional management.[50] Harlan and Zohary noted that wild einkorn 'occurs in massive stands as high as 2000 meters [altitude] in south-eastern Turkey and Iran'.[51] Wild emmer (*Triticum turgidum* subsp. *dicoccoides*) 'grows in massive stands in the northeast' of Israel, as an annual component of the steppe-like herbaceous vegetation and in the deciduous oak park forest belt of the Near East.[52] Anderson recorded wild wheat growing in Turkey and Syria in natural, rather pure stands with a density of 300/m².[53] Anderson's Figure 5 shows a relic stand of wild wheat near a middle-Neolithic site, with a comment on the stand density, 'purity', and lack of other plants.

The stand density of these wild cereals is often compared with fields:

- 'Over many thousands of hectares it would be possible to harvest wild wheat today from natural stands almost as dense as a cultivated wheat field'.[54]
- 'On uncultivated slopes, natural fields of these wild cereals extend over many kilometres. In their growth and total mass, these wild fields of wheat, barley and oats are not inferior to their cultivated counterparts'.[55]
- 'Even now, stands of wild cereals develop as dense as sown cultivated fields when protected from livestock'.[56]
- 'It is therefore possible to envisage a vast expanse of wild einkorn expanding across the erstwhile steppe, and resembling a seemingly limitless, if patchy, field'.[57]

There are similar reports for wild barley (*Hordeum*) and wild oat (*Avena*).

Miller noted that wild wheat in the Fertile Crescent occurred in natural stands as dense as a cultivated field and then suggested that 'it is no accident that the south-western Asian cereals form the basis of modern monocrop agriculture'.[58] Yet supposedly ecological approaches to farming continue to ignore these wild fields.

Ecological determinants of natural monocultures

Although the simple structure of natural monocultures may indicate a suitable model for annual cereal cropping, major questions remain unanswered. What are the ecological determinants of natural monocultures, and can these be reproduced in sustainable, but simple cropping? Answers would allow farmers not just to mimic the structure of natural monocultures, but also to mimic the ecological processes that maintain the stability and sustainability of natural monocultures. Yet these important questions seem not to have been asked.

There has been considerable recent research by ecologists on the role of species diversity.[59] Very little of the newer work takes up the question of why some ecosystems have more species than others.[60] However, May noted that low species diversity is characteristic of unpredictable and 'environmentally buffeted' environments.[61] Diversity was not correlated with environmental productivity: for example, salt marshes and estuaries are examples of low species diversity in productive environments.[62] The wider application of this relationship between low species diversity and high productivity is a key issue for sustainable cereal cropping.

How do these evolving views in ecology on unpredictability and 'buffeting' relate to agriculture? Natural flood and fire regimes are examples of environmental buffeting. At the time of transition between food gathering and cropping, early farmers would have been very aware of the impact of ecological determinants such as fire and flood on both productivity and the structure of natural stands of wild cereals: human existence depended on this knowledge. We suggest that a transition to annual-crop farming that mimicked natural disturbance regimes in early fields would maintain the undoubted robustness of natural monodominant stands. For rice, the 'artificial swamp' of the field reduces competition from weeds and has allowed rice to persist in monodominant stands, as with many grasses in natural swamps. For the seasonally dry grasslands which form a natural model for sorghum, and for wheat and barley fields, seasonal burning or grazing may be the 'fluctuating environment' that gives grasses the competitive advantage which allows an investment in annual seed production.[63] Such parallels between natural and agricultural disturbance were first recorded by the Chinese historian, Ssu-ma Ch'ien, who in 148 BC wrote of the Yangtse Valley, 'where the land is tilled by fire and hoed by water'.[64]

Drawing a specific parallel between natural disturbance and agriculture, Grime described the dominance of *Impatiens glandulifera*, a large summer annual which in Europe colonizes extensive areas where the margins of water courses have been disturbed by erosion, flooding and silt deposition. Dense colonies resulted. Grime suggested that:

> the objective of many forms of arable farming, especially cereal cultivation, is to achieve weed control by creating conditions in which the crop plant attains the status of dominant. As in the example of I. glandulifera, dominance by a cereal crop depends primarily upon the synchronous germination of a high density of large seeds followed by the rapid development of a dense vegetation cover composed of a large number of plants of comparable age and maturity.[65]

More generally, the importance of cereals — that is, grasses — in food production may relate to the ability of grasses to resist disturbance, indeed to thrive under seasonally disturbed conditions. Clayton and Renvoize suggested that:

- grasses are physiologically adaptable to saline, alkaline and seasonally waterlogged soils, forming edaphic grasslands in such environments;
- grasses benefit from a fire regime that is lethal to many other plants, and, having co-evolved with herbivores, can sustain a level of predation sufficient to cripple many competitors;
- grasses have evolved a versatile lifestyle adapted to unstable or fluctuating environments, particularly those associated with strongly seasonal rainfall regimes or the early stages of succession following disturbance.[66]

Diversity within monocultures

The level of within-species diversity in natural monocultures is a further issue of direct importance for agriculture. Monoculture is defined by the International Board for Plant Genetic Resources (IBPGR) as: 'the growing of a single plant species in one area, usually the same type of crop grown year after year'.[67] (The term monoculture is now also used for single-variety fields and, incorrectly, as a synonym for industrial agriculture.) Whatever the usage for fields, it will be important to know the genetic structure within natural monocultures and how it compares with the genetic structure of species found in more diverse vegetation. There are indications that some natural monocultures may be genetically uniform — for example, the many examples of aquatic plants that spread vegetatively — with no intraspecific genetic diversity. It is commonly thought that such a low level of diversity is unsustainable in farmers' fields. How then does it persist in nature?

In contrast, if natural monocultures of wild relatives of our cereals are found to be genetically diverse, then mimicking nature by the use of varietal mixtures could add sustainability to cereal cropping.[68] Several different mechanisms may apply, ranging from complex interactions between more or less susceptible varieties in the face of pests and disease, through to a simple portfolio effect — the different responses of different varieties to different conditions, often claimed as a benefit of traditional varieties. There have been some useful surveys of the genetic structure of wild populations of cereal relatives.[69] In contrast, there has been limited research on natural monocultures of crop relatives to learn lessons for sustainable cereal farming. An exception is Browning, who discovered a multidimensional disease resistance structure in wild *Avena* populations.[70] He subsequently used this knowledge to develop a strategy for managing crown rust of oats in the USA.

Crop-associated biodiversity

Darwin's description of the extreme biodiversity within the natural monoculture of kelp indicates that concern over the ability of crop monocultures to maintain associated biodiversity may be misplaced. If wild monocultures can otherwise be biodiverse, then so too can crops. In fact, there is now substantial evidence that single crops have self-regulation through great crop-associated biodiversity. For irrigated rice, Schoenly *et al* reported a 'staggering taxonomic richness, interconnectedness and spatiotemporal flux', with a 'complex and rich food web of generalist and specialist predators and parasites that live above, below, and at the water surface'.[71] It has been demonstrated that management of the crop cycle to increase detritus from the rice crop could encourage detritus feeders and, in turn, natural enemies of rice pests, contributing to substantial biodiversity in a monoculture and, under most circumstances, minimal pest damage.[72] A review of crop-associated arthropods suggested that extremely high herbivore diversity in large agricultural monocultures showed that factors other than plant diversity may be important in determining local herbivore diversity.[73] At higher trophic levels, including parasites and predators on the herbivores, there is yet more diversity. There is an increasing knowledge and appreciation of crop-associated biodiversity and its role in supporting monocultures.[74] More information is needed from wild ecosystems to indicate whether the associated biodiversity of natural monocultures (for example, in the soil) can or should be maintained by the appropriate field management of crops.

Field management

It is commonly thought that crop diversity is particularly needed in farmers' fields in marginal environments.[75] Yet the prevalence of natural monocultures in what are undoubtedly marginal environments now questions this belief. Characteristically, natural monocultures can be found in climatically marginal conditions, as with the long dry seasons that favour wild relatives of sorghum and wheat. Natural monocultures are also found in geographically marginal conditions, very commonly where land meets water, as with Darwin's kelp beds. There are many familiar examples, as with reed beds of *Phragmites australis* growing at the margins of freshwater lakes in Europe (stands of *Phragmites* can have an age in excess of 1,000 years).[76] Salt marshes on the margin between land and sea in Europe and North America are often dominated by species of the grass genus, *Spartina*. Net annual primary productivity of *Spartina alterniflora* marshes has been reported as up to 6,000 g m^{-2}, a figure close to the highest dry matter yields of intensively managed arable crops.[77] Significantly, the same report argued that many of these *Spartina* marshes 'consist of extensive monotypic stands of no greater complexity as ecosystems than a field of an arable crop'.

However, monodominant swamp vegetation raises another factor of potential importance for the management of cereal fields — the annual input of nutrients through silt and flood. As noted above, swamp vegetation has relatively high productivity, attributed to a plentiful supply of nutrients, due to flushing with nutrient-rich water. A feature of many natural monocultures — including Darwin's kelp beds, and swamp and estuary vegetation — is an external supply of nutrients. Allan thought that agriculture originated in the flood plains of large rivers and that: 'This is not at all surprising, for these soils are the most persistently fertile in the world: they have an almost inexhaustible supply of available plant nutrients brought down from the upper lands drained by the rivers.'[78]

The ecosystem service of nutrient capture is a feature of flooded rice production. Indeed, most of the world's rice grows on alluvium and annual silt deposits from the Himalayas. Greenland noted the sustained production of rice in the broad river deltas of Asia, dependent on the nutrients and fertile sediments carried with the seasonal floodwaters.[79] Indeed, in Bangladesh, the more severe the flood, the better the subsequent rice harvest. Can the argument be made that the application of fertilizers by rice farmers old and new is a mimic of the natural nutrient enrichment regime under which wild relatives evolved?

Lessons from nature?

If farmers have transferred ecological determinants of monocultures (including stress, disturbance and nutrient addition) from natural models to fields, crop adaptation to such ecological mechanisms will be longstanding, dating back millions of years, rather than the few thousand years since crop domestication. A working knowledge of these mechanisms, therefore, will be a bonus for sustainable cereal farming under changing conditions. In addition to abiotic determinants, there will be a range of biotic interactions. For example, what is the role of associated plants in otherwise monodominant wild stands? There is the belief that without crop diversity, unfilled ecological niches will allow weed growth.[80] Is this always so? Here there is the chance of learning directly from nature. The mechanisms by which simple, productive and robust natural stands of wild relatives of cereals exclude competing species could be of extreme value for agriculture, beset with problems of weeds (apart from sleeping, most human time is spent weeding). The lack of natural methods of weed control is a significant problem to the success of organic agriculture. No-till farming is a modern example in which the stress of herbicides is applied to maintain fields weed-free. What are the natural stresses that maintain monodominant vegetation free of competitors in the wild? Can they be mimicked in fields?

Agricultural origins

There is a common belief that cereals arose as weedy annuals: 'colonizers of the weedy ground around the campsite'.[81] This essay supports a contrasting hypothesis for the origin of cereals: that of early farming based on the model of robust, simple and natural ecosystems, rather than transient, weedy and anthropogenic ecosystems. The importance of the chronological link between dense stands of wild cereals and the origins of cereal agriculture has been repeatedly emphasized.[82] Further, the model of dense stands of cereals (which were already known as a seasonally important food resource in South-west Asia) would have been an obvious entry point to agriculture for the first cereal farmers and, indeed, this has been suggested often.[83] Opinions differ as to the location of the transition from dense, natural stands to fields. One suggestion is that this happened *in situ*, by maintaining or improving the resource in the original locality.[84] In contrast, it has been argued that wild cereals were transplanted from their natural fields to new areas as human settlements dispersed.[85] Earlier, in an extensive review of 'environmental ennoblement' by pre-farming communities, Yen presented evidence that there was a manipulation of the environmental settings of favoured food species: a 'domestication of environment'.[86]

For rice, if early farmers chose swamps first to gather, then to farm wild rice, they would be working in habitats where 'natural monocultures' were common. Allan argued that: 'Systematic agriculture . . . may have begun in the floods plains of the great rivers — first by utilising the natural floods and then by controlled flooding or irrigation, for the step from one to the other is natural and not very difficult'.[87] Under this view, the earliest cereal farmers were not only effective plant breeders (now widely accepted) but also knowledgeable applied ecologists.

It is commonly assumed that there has been a progressive simplification of agroecosystems to monocultures during the evolution of agriculture.[88] In contrast, we believe that at least one domestication pathway has mimicked natural monocultures from the start (and continued to do so: 6,000 years ago the first farmers in Europe sometimes grew emmer as a pure crop, and spelt wheat was apparently grown as a crop by itself).[89] If natural monocultures were successfully mimicked — and the above evidence clearly suggests so — the ecological insight of early farmers in understanding the determinants of natural monocultures should be respected rather than cast aside with calls for the wholesale replacement of monocultures in today's farming. Indeed, a study of natural monocultures could offer insights into the ecologically sound management of present-day cereal fields.

In a challenge to ecologists, Blumler noted that 'dense stands of wild cereal are a paradox and a puzzle'.[90] It is a tribute to the staying power of arguments for diverse and perennial agriculture that Blumler's paradox has been ignored or rejected. This essay attempts to resolve the paradox by supporting one obvious hypothesis for crop origins — through the skilled choice and then management of monodominant annual stands of wild cereals by early farmers.

Which 'harmony with nature'?

Hitherto, there have been repeated and generic claims that sustainability results only from complex cropping patterns that mimic complex perennial, natural ecosystems. This essay does not question that in some environments this may be true. For example, there may be sound ecological reasons for farming structurally complex fields in the biotic maelstrom of humid, tropical lowlands.[91] However, the management of annual cereals such as rice, sorghum and wheat — producing most of our food — appears to originate directly from far simpler natural models, represented by monodominant stands of wild relatives in seasonally perturbed environments.

Before simple, natural models can contribute to sustainable farming, we need answers to many questions. A recent workshop on 'Agriculture as a Mimic of Natural Systems' asked how could we relate the structure and function of a mimic system 'when so little is known about the underlying processes that confer persistence and resilience on the natural system on which the mimic is based?'[92] Thus there is an urgent need for research on natural monocultures — preferably on the annual relatives of our most important cereals such as rice, wheat and sorghum. We need to know:

- The genetic structure of natural monocultures: are they genetically uniform or diverse?
- How does the level of genetic diversity relate to persistence under pest and disease pressure and to short-term adaptation? Can this provide lessons for sustainable farming?
- What are the ecological determinants of natural monocultures? Does their ecology always include natural stress or disturbance (such as burning or flooding) or external nutrient supply (as found in aquatic natural monocultures) that could provide guidance for field management?
- What is the role of a 'natural monoculture' in the landscape, and the significance of biotic interrelations with surrounding vegetation?
- Were natural monocultures an ecological pathway to domestication? If so, can their ecological history (which long pre-dates domestication) contribute evolutionary stability to crop production?

This last issue is of great importance for sustainable agriculture. Early farmer-ecologists certainly had a detailed knowledge of natural ecosystems as a source of all human food. They could have used this ecological knowledge to craft fields 'in Nature's simple image'. If the farming of major Old World cereal crops — including rice, sorghum and wheat — is, as seems probable, closely based on simple, natural models still present in the regions of cereal domestication, farmers through ten millennia have maintained an ecological pedigree for cereals that stretches back millions of years (both an 'evolutionary' and an 'ecological' continuum between ancestral species and crops has already been suggested).[93] This idea offers an ecological and evolutionary transition from wild ecosystems to the first cereal fields. Rather than an abrupt and unsustainable dislocation from nature, we suggest that cereal agriculture over ten millennia has been a continuation of the natural order. But for agriculture to 'proceed in harmony with nature', as recommended by Prince Charles, far more research is needed on simple, natural models — wild cereal fields in nature.

Food security and nature's fields

If cereal monocultures can be demonstrated to have a long ecological and evolutionary pedigree, then generic recommendations that monocultures should be replaced by polycultures could be profoundly unnatural and therefore a questionable approach to sustainable food security.[94] In contrast, if ancestral cereals are pre-adapted in the wild to growing in monodominant stands, we should be able to manage our present monocultures in a more sustainable way to enhance food security. However, to achieve greater sustainability for cereal production, considerable genetic and ecological information is needed from nature on the structure and persistence of natural monocultures of crop relatives.

Wild relatives are of increasing value to plant breeders as a *genetic resource* as new needs are matched with new breeding technology. In future, dense stands of wild relatives of cereals — nature's fields — may also be an important *ecological resource*, providing information for the sustainable management of simple fields. The present neglect of dense stands of cereal relatives needs urgent correction — most obviously by research in the regions of origin of cereals. At least for most wild rice species, it may already be too late: floodplains have been embanked and wetlands drained and converted to farmland throughout South-east Asia.

The success of traditional farmers in translating the flooded ecology of wild rice from river valleys to crop terraces high in mountains (a feat now recognized in a World Heritage 'cultural landscape' designation for the Banaue rice terraces in the Philippines) suggests that farmers have a detailed, but hitherto unquantified, knowledge of mimicking natural ecosystems in their fields. Can ecologists learn enough from traditional farmers and from simple nature to support the continued productivity of simple fields?

Over the next 50 years there could be 4 billion more people to feed.[95] Nearly all these extra mouths will be in developing countries, where crops were domesticated and 'nature's fields' still exist. There is an urgent need for agricultural policy and research to consider the full range of possibilities for increasing productivity and sustainability, from simple to complex fields in simple to complex farming systems. Ecological approaches to agriculture must become more inclusive. An emphasis on polycultures alone will not suffice.[96] The ecology of 'nature's fields' — tested through time, and stable and sustainable by definition — is an untapped and highly relevant resource for cereal farming, which still produces most of our food. Simple fields of wild rice, wheat and sorghum, in Asia and Africa, have played a vital role in our greatest human achievement, the development of agriculture. They remain neglected or ignored.

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