Perils of production with perennial polycultures

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Abstract

Perennial grains and polyculture were proposed (Renewable Agriculture and Food Systems 20 (1), March 2005) as alternatives to annual grain systems. The authors criticized current annual systems as unsustainable and pointed to native prairies as a model sustainable system with no added input and little negative environmental impact. That portrayal is shortsighted. All previous efforts to breed perennial grains have resulted in crops incapable of supporting both a perennial life-habit and grain yield sufficient to address food needs. Analyses of production/uptake and partitioning of C and N resources within perennial crops confirm that a trade-off between the C and N needs of perennation and grain yield will limit efforts to create productive perennial grains. As a result, incorporating perennial life-habit into grain crops would severely constrain world food production unless the area put to farming was greatly increased. In addition, pest- and risk-management problems, which escalate when sanitizing benefits of crop rotation are abandoned, are exacerbated in polyculture. Although grains contain only small concentrations of nutrients, the amounts exported in crop yields are large. If yield is to be maintained, external inputs are essential, regardless of life-habit. Polycultures of perennial grains are seen to have little potential for producing sufficient food to serve as alternatives for current production systems.

Keywords

Perennial grains, polyculture, nutrient extraction by grains, trade-off

Introduction

Several papers published in the March 2005 issue of Renewable Agriculture and Food Systems (RAFS) (DeHaan et al., 2005; Cox et al., 2005; Crews, 2005; Glover, 2005) follow a theme that conventional agriculture, as practiced in the temperate zone with annual crops and nitrogen fertilizer, inadequately protects our landscapes and rivers. The authors propose an alternative based on perennial grain crops grown in complex polycultures with a grain legume as the source of nitrogen (N). This view has remained essentially unchanged since it was first outlined by Wes Jackson of the Land Institute (Jackson, 1980), and little progress towards that goal has been made in the intervening years. The presentation by Jackson and Jackson (1999) at the Australian conference on agriculture as a ‘Mimic of Natural Ecosystems’ did provide insights to the Institute’s supporting database, and Cox et al. (2005) and Crews (2005) provide analyses of disease and nutrient issues respectively. Crews’ paper makes clear that yields of unfertilized polycultures cannot be large. In contrast, DeHaan et al. (2005) present a confusing view of “trade-off” while avoiding discussion of its physiological basis. Several themes emerge in these papers. Each involves issues that merit discussion.

Perennial grains

Wagoner and Schaeffer (1990) chronicled the many attempts over the past 130 years at developing agriculturally acceptable perennial cereals. Most efforts involved crossing perennial and annual species followed by selection and breeding for perennial life forms having reasonable longevity, adequate grain size, and yields superior to what is now achieved with annuals. That objective has not been achieved and is clearly a difficult challenge. The goal outlined by Jackson (1980) has made work of the Land Institute even more difficult by spreading its few efforts over a wide range of species and objectives (DeHaan et al., 2005; Cox et al., 2005; Crews, 2005; Glover, 2005; Jackson, 1980). A focus on perennial polycultures, which will require a whole set of new grains rather than just one, also serves to strongly diffuse efforts and hamper progress.

When breeders have obtained perennial progeny from crosses between annuals and perennials, subsequent selection for grain size and yield has invariably had a strong negative interaction with longevity (Wagoner and
Schaeffer, 1990). DeHaan et al. (2005) refer to that as ‘trade-off’ (a term drawn from recent evolutionary biology literature). Trade-off occurred with the population approach employed at The University of California at Davis by Coit Suneson (Suneson et al., 1963; Wagoner and Schaeffer, 1990), and more recently in efforts at the International Rice Research Institute (IRRI) to produce perennial rice for erodable upland sites (H.R. Lafitte, IRRI, pers. commun., June 2004). The effect in rice was strong and the program was discontinued at IRRI but is being continued in China where it may also facilitate seed production of hybrid rice. Trade-off also is seen in promising work at Washington State University (Scheinost et al., 2001), where the objective has been development of a crop that will control erosion on steep land while providing some grain yield (S. S. Jones, Washington State University, pers. commun., July 2004).

**Trade-offs**

The inverse relationship between perenniality and seed or grain yield is an important issue. Like all source-sink relations, it depends upon a simple principle of chemistry known as the conservation of mass: that mass is neither created nor destroyed in ordinary chemical reactions. Similarly, in plants, any use of a finite supply of reduced C (photosynthate), or N, in one activity (e.g. in growth of organs relating to perenniality) reduces the supply available to all other activities including grain growth. Any decline in photosynthesis must diminish growth and/or storage of C. Conservation of mass is a major theme in plant physiology where its role in partitioning of photosynthates can be traced at least to Klebs (1910) and his concept of ‘ripeness to flower’.

Research on photosynthate partitioning has employed proximal (De Vries et al., 1974) and elemental (McDermitt and Loomis, 1981) analyses as powerful tools for calculation of ‘growth yields’ (g product produced per g photosynthate consumed) for individual compounds and broad classes such as protein and lipids, as well as for organs and whole plants. Taking the example in Table 1 of DeHaan et al. (2005), the large amounts of protein (40% of DM) and oil (19% of DM) in soybean [Glycine max (L.) Merr.] will result in a smaller growth yield for soybean biomass (0.65 g biomass per g photosynthate) than for alfalfa (Medicago sativa L.) hay (0.81 g per g). Using these factors to calculate the original amounts of photosynthate required in biomass production of alfalfa and soybean reveals the contrary conclusion that annual soybean is just as productive in original photosynthesis as perennial alfalfa.

Jackson and Jackson (1999) took trade-off as an assumption, however, and detailed an experiment with Eastern gamagrass (Tripsicum dactyloides L.), a perennial C4 bunch grass, which they took as proving that trade-off need not be a problem. Several aspects of that experiment prevent me from reaching the same conclusion. The plants were not grown in swards and yields were expressed per unit basal area of the bunch rather than the much larger extended area of foliage. In addition, the flowering culms extended their leaves well above the main canopy with the result that grain growth was relatively independent of the rest of the plant. Finally, the grain matured in early July leaving at least three months for restoration of substrate levels in the stem bases. (DeHaan et al., 2005) also struggled with this issue but their example from general ecology relates poorly to the plasticity found among sink tissues competing for limited substrate within a plant. Why, for example, do grass plants (and trees) tiller (or branch) abundantly when wide-spaced from competitors while that expression is strongly suppressed in crowded plants? And why must the vegetative growth of fruit trees be suppressed by pruning in order to promote fruiting?

DeHaan et al. (2005) came to two suppositions about trade-off. One is that perenniality, like yield, is a quantitative trait and can be manipulated through simple mass selection. Therefore, simultaneous selection for yield and perenniality could be successful. That argument ignores the law of conservation of mass as well as the long history of failures with that approach (Wagoner and Schaeffer, 1990, and others). These authors also argued that the alternative approach, selection following ‘phenotypic’ models, represents an inferior method. They seem unaware of the enormous progress that has been achieved with cereals through trait selection during the past 50 years. Agronomists refer to models with sets of superior phenotypic traits as ‘ideotypes’. In wheat, for example, stiff straw, short stature, limited tillering, and erect leaf habit were specific targets for selection and all were critical.

**Table 1. Nutrient contents of various grains and forages.** The maize-soybean example is based on state averages for Iowa. Wheat yields are averages for their regions. The forage yields are typical for eastern Kansas. All crops were rainfed except in Mexico where irrigation is common.

| Crop        | Yield (kg grain/ha) | Nitrogen | Potassium | Phosphorus |
|-------------|---------------------|----------|-----------|------------|
| Maize       | 8000                | 139      | 29        | 23         |
| Soybean     | 3000                | 205      | 55        | 20         |
| 2-year total| 11,000              | 344      | 84        | 43         |
| Annual average | 5500               | 172      | 42        | 22         |
| Wheat       |                     |          |           |            |
| UK          | 8000                | 180      | 37        | 30         |
| Mexico      | 5000                | 110      | 23        | 22         |
| USA         | 2500                | 62       | 12        | 10         |
| Alfalfa (Kansas) | 5000             | 146      | 85        | 12         |
| Prairie hay (Kansas) | 3000       | 38       | 32        | 5          |

Notes: Crop yields (0% moisture; rounded) are from USDA Census of Agriculture 2002 and FAO statistics 2002 for UK and Mexico. Alfalfa yield, 2 years after sowing in Republic County, Kansas, is from the web site for Kansas Crop Performance Tests. Yield of prairie plants is the peak in aboveground biomass on upland sites at the Konza tall-grass prairie. Nutrient contents for USA wheat grain (16% crude protein), white wheat for UK and Mexico (14% crude protein) and other crops are from National Research Council (1982). Harvested material contains 1–4 kg Ca per ton for grains and about 14 kg per ton for alfalfa.
to the enormous yield advances that have been achieved with modern cultivars. In mid and lower latitudes, canopies of erect leaves are more efficient in photosynthesis than lax leaves because the degree of light saturation is less (Duncan et al., 1967). Limited tillering and erect leaves permit dense, highly competitive, stands of uniformly spaced plants to produce many more grains per unit area. And shorter straw, as expected, sharply improves harvest index (from ca. 0.35 to over 0.5 for wheat). Efforts towards breeding perennial grains would be greatly assisted by identification of such ideotype traits. In particular, the type of perennation (e.g. rhizome or crown bud) and phasing of vegetative and reproductive growth, and their genetic control, should be established early in the breeding program.

Mass selection of populations as proposed by DeHaan et al. (2005) ignores the fact that genetic control ultimately resides in individual genes. Quantitative trait loci (QTL), which are the basis of such quantitative models, are generally composed of a small number of specific genes. Once those genes are identified, and isolated, they can play powerful individual roles in phenotypic advancement. Olmos et al. (2003) demonstrated that nicely with a QTL for grain protein content in durum wheat (Triticum durum L.).

The second supposition of DeHaan et al. (2005) is that an earlier start in the spring provides perennials with a longer season and more photosynthesis and that this, in turn, would satisfy substrate needs for both perennation and large grain yield. That hypothesis sidesteps several issues. One is that production over a longer season requires greater supplies of water and nutrients. In many places, including the American Great Plains, rainfall commonly limits perennials to production levels similar to what is obtained with annuals. Those familiar with pasture production in the American Corn Belt and Great Plains know that water supply strongly limits seasonal production of forage perennials in most years. In short seasons (drought years, or early frost), there might not be sufficient time to fully replenish C and N supplies in the perennial structures of a grain crop, placing stand density and vigour in jeopardy. Given that herbaceous perennials require one or more years for establishment before they come to full production, considerable risk is inherent in the perennial model. That trade-off risk increases as yield increases. Indeterminate flowering and fruiting, common in annuals such as the dry beans (Phaseolus spp.), offer a practical solution to farming with a variable water supply. If the seasons are reliably longer, annuals with a longer cycle can be used or the land can be double cropped.

DeHaan et al. (2005) take production of 8900 kg dry fruit per ha by banana in Central America as evidence that perennials have sufficient photosynthetic production to overcome trade-off. Good yields of banana are not unusual given their parthenocarpic (seedless) nature and very small protein content. Established C4 Napiergrass (Pennisetum purpureum Schumacher) can produce 85 Mg of aboveground dry matter per ha in a year in El Salvador (Loomis and Gerakis, 1975) and C3 alfalfa reaches 30 Mg dry forage per ha in California, but neither is a good producer of seed even after establishment.

Annual grains mobilize almost everything except wall material from vegetative parts (leaves, stems and roots) during reproduction. ‘Almost everything’ includes most minerals, lipids, carbohydrates, and proteins (a principal source of N for grain formation). With wheat and maize, that leads to harvest indices near 0.5 on a mass basis (g grain per g crop biomass) and near 0.7 on an N basis (g N in grain per g N in crop). As a result, annuals deliver more grain yield per day of growth, per mm water transpired, and per kg N acquired than is possible with perennials. Another result is that the residues of annual crops are generally very low in N.

The N economy of perennials is different. Reproduction generally occurs in midseason when supplies of C and N substrates must come mainly from current production. But those amounts are less than annuals are able to mobilize through whole-crop senescence, and grain yields of perennials will inevitably be less than those of well-bred annual grains. Nitrogen remaining in vegetative tissues or acquired after reproduction may serve as substrate for next year’s growth. At the end of the season, it is mobilized by senescence and stored in perennial organs (stems bases, rhizomes, or tuberous roots). Thus, perennial grains will face trade-offs for N as well as C substrates. The trade-off for N may be even more limiting to perenniand and grain production than the C trade-off we discussed earlier.

Trade-off is also illustrated in data presented by Young (1990) for a large group of species. Those data reveal that relative partitioning to reproduction in a single, fatal, reproductive effort (semelparous plants) was nearly three times that of related species that reproduce repeatedly (iteroparous plants). Young (2002) offered a simple demographic model that explained conditions under which evolution of semelparity, which has occurred repeatedly, would be favoured. Conversely, if it were possible for a perennial to achieve something approaching the reproductive effort of annuals, we should expect that evolutionary processes would have found it (Denison et al., 2003).

Is the prairie polyculture concept useful?

Polycultures are not unusual in agriculture. The chief example is the widespread use of mixtures of perennial grasses as forage crops and in pastures. Legumes in the mixtures serve as a source of N. A forage mixture appropriate for temperate sites might include cool- and warm-season grasses and a warm-season legume. That system provides low-cost and nutritionally balanced forage and grazing. By capturing the full length of the growing season, the mixture achieves greater annual productivity than any one of the species alone, providing supplies of water and nutrients are sufficient. Season extension is also the basis for overlap cropping (a second crop is seeded as the first matures) and double cropping of annual grains practiced in tropical and subtropical regions. Mixtures of two or more species (e.g. cassava (Manihot esculenta Crantz) intersown with bean (Phaseolus spp.)) is employed in slash and burn agriculture practiced over 1 billion ha in
the tropics, but it supports only about 40 million people (Giller and Palm, 2004).

Wes Jackson (1980) took inspiration for polyculture from prairies, which also maintain green cover over most of the growing season. He has written of the beauty of natural prairie and his presumptions about high productivity, stability, limited erosion, and tightness of nutrient cycling in those systems. Perennation (with continuous protection of the soil and deep rooting) and diversity are held to be responsible for most of those benefits (Glover, 2005). These ideas launched the Land Institute’s efforts to achieve similar benefits for agriculture through a prairie-mimic polyculture.

The papers by Cox et al. (2005); Crews (2005), DeHaan et al. (2005) and Glover (2005) expressed admiration for the dense root systems of prairie perennials. But the authors overlooked some important points. One is that such rooting develops slowly over several years. Another is that rooting habits are very plastic, reflecting a trade-off between roots and shoot that has been termed ‘functional equilibrium’ (Brouwer, 1983; Loomis and Connor, 1996). The equilibrium reflects a tendency for suppression of root growth due to a shortage of C substrate when shoots that are well supplied with nutrients and water grow rapidly. Conversely, when soil resources of water or nutrients are limiting, shoot growth is suppressed more than photosynthesis. Carbohydrate accumulates and root growth is then well supported. In that way, rooting systems of annuals adjust to the consumption of nutrients and water by shoots.

Another point is that annuals generally have much more robust root systems than the sparse, shallow rooting that DeHaan et al. (2005) and Crews (2005) depicted in highly inaccurate drawings. Given appropriate conditions, annuals root profusely in fertile surface layers. On deep soil at Davis, California, and without irrigation, sugar beet roots attain 4 m depth during the first year compared with 3 m by maize and 2 m by wheat. And prairie perennials can be shallow rooted. The monumental studies of the rooting of prairie plants by Weaver (1968) merit consideration. His publications spanned over 50 years (1915 to 1968) and allowed him to generalize that roots of perennial grasses not only required several years to reach their full extent but that turnover averaged a considerable 40% per year.

Tight recycling of nutrients is largely a matter of circumstances. With their aerodynamically rough canopies and long season of green cover, prairies generally exhaust the soil water supply. As a result, water shortage is common, annual production is variable, and little or no soil drainage occurs except in years with abundant precipitation. In addition, very small amounts of nutrients actually cycle through prairie systems; productivity is low and the nutrient content of biomass is small (Weaver, 1968) (also see Table 1). Nitrogen cycles poorly in prairies, and N deficiency is a common cause of low productivity (Risser et al., 1981; Knapp et al., 1998). Deficiencies occur because N is strongly sequestered into humus as grass roots and litter decay, and because losses of N occur by gasification during prairie fires, and through denitrification, as well as leaching. Annual N inputs in rainfall are about equal to those losses (Risser et al., 1981; Blair et al., 1998).

The low and variable productivity of prairies has been confirmed in many studies, most notably, perhaps, those conducted under the International Biological Program (IBP) (Risser et al., 1981; Sims and Singh, 1978). The IBP work revealed that aboveground biomass was commonly about the same as crown material, and much less than root mass. Recent studies have yielded similar results. A rich site at the Konza prairie (eastern Kansas) had 6300 kg of biomass per ha aboveground and 19,000 kg per ha belowground (Sims and Singh, 1978). In the IBP work, net primary production of tall grass prairies in Nebraska and northern Kansas was very modest and about equally divided between above- and belowground compartments. The prairie rate (5 to 6 g biomass per m² per day) was much less than the rate observed for good maize crops in the same region (more than 15 g per m² per day). Low production rates by prairies indicate poor use of water and sunlight resources compared to wheat and maize crops. Furthermore, stability is poor because interannual variations in supplies of moisture and nutrients lead to very large fluctuations in production and species composition.

In summary, the prairie model is seen to have small harvestable productivity while putting its ‘eggs into the wrong basket’ through over-investment in crowns, root systems, and humus. It may be just another example that natural ecosystems, in fact as well as in theory, generally offer very little as models for output of human-edible product (Denison et al., 2003).

**Stability, risk, and management of polycultures**

**Species composition and stability**

The Clementsian concept of plant communities (and ecosystems) as ‘super organisms’ (Whittaker, 1975) is implicit in the Jackson (1980) prairie model. That now-obsolete concept tends to overlook the performance and fate of component populations. A community may appear relatively constant in appearance (physiognomy) over time even though component species are quite unstable in the sense of persistence or productivity. Weaver (1968), among others, reported numerous cases of rapid change in species composition of prairie sites in response to fire or interannual changes in rainfall or temperature. In areas where rainfall generally exceeds annual potential evapotranspiration (PET), prairies represent arrested seral stages. In tall-grass prairies of Iowa with which I am familiar, populations fluctuate over large ranges but the communities persist as prairie if they are burned periodically. Without fire, they progress rapidly to woodland. Similar species instability is seen in pastures seeded with grass-legume mixtures (Brouwer, 1983). There, legumes dominate in areas with poor N supply while grasses dominate
where N is abundant. As a result, patterns of legume abundance and activity shift continually.

With low fertility, yields of polyculture communities can sometimes exceed the yield of pure stands of their components. Such over-yielding occurs when the species occupy different niches (e.g., legume vs. nonlegume, or deep-rooted vs. shallow-rooted plants) and one species compensates for poor performance of others. Trenbath (1999) argued, using data for annual polycultures, this would be an advantage in subsistence farming on poor soils because of increased stability of the small total food supply. As fertility improves, however, possibilities for niche differentiation disappear and one species usually dominates the community (Loomis and Connor, 1996). Community stability is then similar to that of a monoculture.

Any factor with differential effects on component species of a polyculture will affect performance of the culture. Flood, drought, severe winter, fire, insects, disease, fluctuations in nutrient supply (including fertilizer additions), and soil acidification are among the factors that affect some species more than others. Add natural variations in life span, and trauma caused by harvest or grazing, and it becomes clear that choosing appropriate species and cultivars for a polyculture, deciding on optimal densities, and implementing a management scheme represent very difficult challenges (Loomis and Connor, 1996; Trenbath, 1999).

Farmers would have few tools for risk management with a polyculture of perennial grains. For example, a change of cultivars (to cope with a new disease) or species (to meet market demand) would require reseeding the polyculture while losing an entire growing season to re-establishment. By contrast, such changes are accomplished easily with annual monocultures where it is even possible to make last-minute decisions about cultivar, date of sowing, spacing, and starter fertilizer. Any weakness in persistence by one species in a polyculture is an invitation for weedy species to invade the stand unless another member of the community assumes the space. After establishment, farmers would have difficulty adjusting composition and controlling weeds. If overseeding were ineffective, light mowing or cultivation at critical times might reduce the population of an overly abundant species and a light dose of herbicide might achieve the same goal. In some cases, the only effective solution, however, would be to start over (i.e., cultivate and reseed).

Full-season green cover by a polyculture will result in maximum seasonal use of water. One result is large rainfall-dependent interannual variations in productivity (Loomis and Connor, 1996; Weaver, 1968). As noted above, it would also have important implications for persistence. Maximum use of water also limits drainage (and nutrient leakage) but it annuls important management options possible with annual crops and predictions of nutrient requirements become inaccurate. Choices about life spans and season(s) within which annuals are grown provide compromises between achieving a reasonable yield, and safety from extreme soil water deficits. Winter wheat fills that role over much of Kansas whereas perennials suffer from water shortages there in most years.

Harvesting also imposes problems. Forage polycultures are harvested very simply and in bulk but grain polycultures will be a quite different proposition because markets typically exist for each grain but not for mixtures. One option would be to use grains with wide separation in phenology so that they would mature and be harvested at different times. That would be difficult even with just two entries, particularly within a short growing season in the temperate zone. It would magnify the expense of harvesting as well as the extent of traffic damage (trampling and soil compaction) compared to the single harvest of a monoculture. If all species were to mature at about the same time (rather difficult to arrange in a variable climate), a single harvest would suffice. That would need to be followed by an expensive mechanical separation process. Bulk harvest would place a premium on shatter resistance since maturity would vary among species. Green tissues would be present in the harvest from any perennial system and would greatly complicate grain harvesting. Finally, in polycultures, the yield of the most-needed commodity is diluted and the presence of other species obscures efforts to manage it properly.

**Managing disease**

Most disease and insect problems tend to be specific to particular crops. Cox et al. (2005) provided a useful analysis by focusing on the diseases that might plague perennial wheat. Options for crop rotation and incorporation of residues are much less with perennial polycultures than with annual monocultures. As a consequence, Cox et al., saw possibilities for increases in problems related to soil- and residue-borne pathogens, and for slow decline due to accumulation of diseases over time. Residue reduction, perhaps by burning, will be necessary. But burning entails a number of problems. In addition to air pollution, scarce supplies of N are volatilized, valuable ash minerals (e.g. Ca, K, and P) are exposed to erosion by wind or water, and the crops might be damaged (Blair et al., 1998).

Some diseases such as leaf and stem rusts exist in numerous races that vary in frequency over years. It has generally not been possible to include resistance to all races within a single cultivar. For annual wheat, most breeders depend on including as much vertical (specific) resistance as possible coupled with strong horizontal (quantitative) resistance. With advance warning of increasing frequency of a particular race, annual cultivars resistant to that race can be deployed. By those means, foliar diseases have been kept to tolerable levels. But those approaches will be less effective with perennial wheat because the duration of crop may extend over several race cycles. Cox et al. (2005) concluded that polycultures would need to depend more on mixtures of cultivars in which each carries different major-gene resistance. The principles behind the use of such mixtures is that some lines will be resistant and yield well while also slowing secondary spread of disease to susceptible lines.

Use of mixtures of cultivars and of multilines is not without problems. They are effective against relatively few diseases and they work best in situations where secondary spread is important, as in large fields and with sparse
animal protein per capita reached its historic minimum World at that time. In the United States, the production of famine and starvation were common in many parts of the inputs of N. It is amazing how readily we forget that fifty years ago, when the human population was only 3 billion, and N and other fertilizers were not widely avail-
fertilizer amounts to only half of the 344 kg N per ha that is
inoculation (Mundt, 2002). In addition, there is a significant increase in breeding expense and past cultivars but that entails variations in phenology and lower performance unless breeding keeps pace on the older entries. In the case of multilines, breeders must develop several versions of each cultivar, with each version carrying different specific resistance. A second problem is that no matter which race occurs, mixtures almost always include susceptible cultivars or lines that diminish total yield. Hence, the mixture cannot perform as well as the most resistant single line (Kampmeijer and Zadoks, 1977).

A little-appreciated problem for breeders is that lines for perennial polycultures need to be evaluated in communities against competition of the type they will encounter in the polyculture. In practice, this requires testing at various densities in polyculture stands during and after establishment – a slow and expensive process compared to tests necessary with annuals in monoculture. With only perennial legumes presently available, any new perennial grain will need to be tested in some artificial system or in simple two-component mixtures. Doing this for cultivar or multiline mixtures will magnify costs. Despite these difficulties, Cox et al. (2005) concluded that while disease management will be difficult, adequate control can probably be achieved if the mixtures carry good levels of resistance.

**Nutrient requirements**

A basic postulate from Glover (2005) and Crews (2005) is that polycultures with legumes as the N source will offer stable and sufficient output of grain, with little need for input of other essential nutrients in fertilizers. Effectively they would depend on wet and dry deposition, weathering of parent material, and efficient cycling for an adequate supply of mineral nutrients.

Those ideas raise important questions about yield level. Are we looking for an alternative to “massive” use of N fertilizer that Glover (2005) and Crews (2005) decried? Or, as Cox et al. (2002) indicated in an earlier paper, are we dealing with a ‘natural system’ for marginal lands that would contribute only marginally? Or as Scheinost et al. (2001) hoped, a system suited to a special niche on steep fertile loess? Cox et al.,’s (2002) theory of natural-system agriculture parallels the so-far futile efforts by international agricultural centres to produce cultivars suitable for soils that are very acid or extremely low in nutrients. If such research were successful, it would lead to further destruction of marginal wildlands (Giller and Palm, 2004), especially in developing countries with grain deficits.

But Glover (2005) also pointed to the need to feed 8 to 10 billion people. Can that be done without fertilizer? Fifty years ago, when the human population was only 3 billion, and N and other fertilizers were not widely available, farming depended mainly upon legumes and rainfall for inputs of N. It is amazing how readily we forget that famine and starvation were common in many parts of the World at that time. In the United States, the production of animal protein per capita reached its historic minimum and there was widespread discussion of the protein deficiencies and possible brain damage in children. A minimum per capita food supply for a year, measured at the farm gate, may be represented by the energy and protein contents of 500 kg grain. That amount provides an ‘original, on-farm’ supply of 23 MJ (5500 kcal) food energy per capita per day and three times our daily protein requirement. It allows latitude for planting seed, waste, processing, and use of some land or grain for other foods (Loomis and Connor, 1996). The World currently produces 2000 Tg grain from 674 Mha or nearly 3000 kg grain per ha, which amounts to 333 kg grain for each of our 6 billion people. Yield will have to increase to 5000 kg per ha to maintain that same standard for 10 billion people — or the area would have to expand to 1120 Mha (see also Cassman et al., 2003). In the, USA, grain yields average 5900 kg grain per ha (2800 kg wheat per ha is augmented by 8600 kg maize per ha) but 7% of our grain production goes to ethanol, 25% is exported directly, and another 12% is exported in the form of meat products.

The importance of these yield questions is seen with data on nutrient contents of various grains and forages presented in Table 1. The maize-soybean rotation that dominates the American Corn Belt is emphasized using averages for Iowa. That system is a principal user of fertilizer N in the USA. Data for average yields of wheat, alfalfa and prairies are also included. Yields in the table are average values currently attained by farmers.

Crews (2005) explored whether nutrients such as Ca, P and K could be supplied by weathering of soil parent materials. (He refers to such nutrients as ‘lithophilic’ but if mineral nutrients ‘loved’ rock, the oceans would not be salty. ‘Lithogenic’ is a more appropriate term except that some, like S, are mainly input from the atmosphere.) Crews notes that likely values for annual P release by weathering are in the range 0.5 to 1 kg P per ha, although 5 kg P/ha might be possible in some cases. But the gap between 1 to 5 kg P per ha and exports of P indicated in Table 1 is large, explaining why fertilizer P is needed on most farmed soils. Similar problems occur with potassium. Arable soils in the USA, even those formed on tills of the most recent glaciers, are largely composed of well-weathered secondary minerals and thus are low in both P and K. That gives emphasis to Crews’ point of identifying places where young soils with high nutrient-release rates might be found. Places, for example, with recent volcanic activity. But that amounts to only a small fraction of the World’s arable lands.

The maize-soybean example also is instructive in another way. The average application of N fertilizer to maize crops in Iowa has declined gradually during the past 15 years to near 135 kg N per ha (Cassman et al., 2003) (with 110 to 135 for maize after soybean and 135 to 160 for maize after maize). It is popular among some commentators to claim such amounts are excessively large. It is well to keep in mind, however, that the 135 kg N is added to a plough layer (30 cm deep) of soil weighing about 1.8 Gg. And in the present example, 135 kg N fertilizer amounts to only half of the 344 kg N per ha that is
exported in maize and soybean grains. As outlined in Table 2, a 2-year N balance can be achieved with inputs in the form of fertilizer, N fixation (legume and free-living cyanobacteria), residues, wet and dry deposition, occasional rotation with leguminous forage on sloping land, and manure. Use of forage-crop rotations and manure-generating livestock vary from region to region and farm to farm. Soybean, as is the case for most grain legumes, is a net consumer of soil N and returns little N to soils in residues. The smaller N fertilizer rate needed for maize after soybean, although called a ‘credit’, reflects the small amounts of soybean residues and thus a small N immobilization term.

Table 2 combines firm data (state-average yields and N rates, N contents of tissues, and harvest indices) with rough averages for N fluxes (wet/dry deposition, gaseous losses). The purpose is to illustrate the magnitudes of N transfers that must occur even in average crop fields. We know that mobilization and immobilization fluxes involve large amounts of N (including fertilizer N), but good data are scarce. Bacteria immobilize residue N, NH₃ and NO₃ into bacterial biomass and humus during decomposition of residues (including roots) and mobilize it through mineralization of those materials. The amount of N held by just microbial biomass can easily exceed 100 kg N per ha (Loomis and Connor, 1996; Blair et al., 1998). Depending upon farming practices, immobilization and mineralization fluxes come into approximate balance after 80 to 100 years of farming (Stevenson, 1982). Immobilization results in an apparent reduction (sometimes to 50% or less) in recovery efficiencies for N fertilizer, a point overlooked in most analyses.

**Nitrogen supply**

Whether significant transfers of nitrogen can occur from a legume to other plants in a polyculture is an important issue. Crews (2005) gave attention to models of the efficiency of such transfer for hypothetical perennial grain legumes. One problem is that death and decay of roots, nodules, and shoot material is the principal (perhaps only) path by which N is transferred from legumes to nonlegume companions. In pastures composed of perennial ryegrass (*Lolium perenne* L.) and Ladino clover (*Trifolium repens* L.), for example, grazing results in death of legume roots and ‘sloughing’ of nodules. Nitrogen release occurs as those tissues decompose. Another major path occurs with animal excreta but that results in patches with massive over-fertilization. Ammonia volatilization and nitrate leaching ensue. Leaching leads to intense local soil acidification (Weaver, 1968; Helyar and Porter, 1989).

Crews (2005) offered two interesting ideas to stimulate N release by a grain legume: selective cutting of the legume to simulate the grazing effect seen in pastures; and a 2-year rotation of grazing and harvesting. N released in the grazing year would presumably support grain production in the following year. The rotation is worth trying even though it would probably increase nitrate leaching and average grain yield would be small. Subjecting a forage legume to grazing-type injury during the annual grain harvest might give a better result but how could it be accomplished? An even better idea might be to return to the proven system of rotation with legume forages such as alfalfa. But when legume crops are used for N production, whether in mixture or stand-alone, they take space, time, water, sunlight and nutrient resources that might have been used by the main crop. One result is that dependence on legumes as the source of N sharply increases the amount of arable land required to feed a given population.

In addition to the trade-off for N that surely will be encountered with perennial legumes, Crews (2005) outlined an additional issue – how to avoid aggressive acquisition and use of mineral N by the legume. That trait, like trade-off, is probably deeply entangled in evolutionary history and is unlikely to be overturned easily. It is necessary during early phases before nodulation, it is an effective ploy in intra-plant competition, and it avoids the disadvantages of fixation, including costly use of C substrate and difficult problems with control of internal pH. Whether the heavy demand that legumes place on soil supplies of P and K is related to pH control remains to be seen. In addition to the internal pH problem, N fixation by legumes results in soil acidification at the same rate per unit N as does use of ammonia fertilizer (Helyar and Porter, 1989; Loomis and Connor, 1996).

Legumes can be their own enemies and they present a set of problems that could be unmanageable in a polyculture. The Land Institute’s hope of solving the N problem with grain legumes won’t be achieved easily, if at all.

**Control of nitrate**

Increased flux of nitrate from landscapes into rivers has been related to several sources including agricultural activities, which has been credited as the source of about 50% of that flux. As a result, fertilizer N is now a popular focus for environmentalists; Glover (2005) and Crews (2005) cite such papers as the starting points for their reports. But
those papers contain mistakes about trends in fertilizer use in USA (and in Iowa) and nitrate pollution, and about the impact of fertilizer on diet and health. My reasons for presenting Tables 1 and 2 is to illustrate that large amounts of N inevitably circulate in crop systems, even those with only modest yield, and that fertilizer input is a modest part of that circulation.

As revealed in Table 2, fertilizer amounted to only 43% of the external inputs of N (fertilizer, fixation, and wet/dry deposition). Even without accounting for considerable immobilization of fertilizer N, it equals only about one-fourth of the mineral nitrogen present in the system during a year, a dramatically different conclusion than was presented in Crews’ Fig. 1.

The entry for maize in Iowa in Crews’ Table 1 is also unrealistic. That result came from a heavily over-fertilized site (187 kg N/ha vs. extension recommendations for 135 kg N/ha or less) (Jaynes et al., 2001). In addition, the site had been reclaimed from wet prairie only 45 years earlier and thus would have a generous mobilization flux from old organic matter (Stevenson, 1982).

As Keeney and DeLuca (1993) pointed out, the presence of nitrate in Iowa streams is related more to general agricultural activity than to fertilizer. Furthermore, nitrate-N levels in the Des Moines River in the 1990s (near 6 mg per l) were similar to that observed in the 1940s. By 1940, the vast reserves of humus N that had been sequestered in soils under prairie vegetation had mostly been depleted to lower equilibrium levels (Stevenson, 1982). There was little use of fertilizer N in Iowa and farming depended for N mainly on legumes, wet/dry deposition, and manure. (Manure was more abundant then because most farms had livestock.) As long as the principal business of Iowa is to produce an abundance of crops, large amounts of mineral N will cycle in its fields. The same will occur in perennial polycultures if they can be brought to yield levels that will contribute significantly to food supply. Some nitrate movement into streams is then almost inevitable. Although those levels continue to decline in Iowa streams, they are still too large.

**Summary**

The great famines of Asia are now 40 years in the past but without control of population and/or greater production, such famines will return (Cassman et al., 2003). Providing food has made continued growth of the human population possible but it has never been an option for agriculturalists to turn away from that need. Attention to population control must come from everyone. If those proposing perennial grain and polyculture crops, wish to substitute a new system of cropping on a signficant portion of the World’s (or even USA’s) arable land, they must aim for quite large yields. And they must do it quickly. Failing that, very much larger areas will need to be farmed, or very large numbers of people will need to go with less food, in many instances, to the point of starvation. Several conclusions can be drawn about whether the development of perennial wheat and grain legume crops for use in polycultures might meet that challenge better than rotated annual monocultures.

- Season-long green cover results in maximum use of the water supply. Without irrigation, perennials face water deficits more frequently than annuals, have greater interannual variations in production, and produce less grain per mm of water transpired than do annuals.
- Season-long green cover, providing water and nutrient supplies are adequate, allows perennials to produce large amounts of biomass and accumulate N but much of that production and much of the N is reserved to perennial structures.
- There is no way to avoid the compromise between perenniality and yield faced by perennials. Attempts at increasing grain/seed yields of perennials have invariably reduced persistence.
- Management of polycultures is more difficult than for monocultures and the difficulty and knowledge required increase geometrically as numbers of species increase. It is simply not possible to simultaneously optimize conditions for all species. For example, space relations in polyculture change with time and few tools exist for adjusting the growth of one species relative to others. In contrast, annual crops can be grown at times and at precise densities that fit with water and nutrient supplies and the crop’s developmental traits. In addition, annuals allow for crop rotation, a powerful management tool.
- Disease management will be more difficult with polycultures than with annual monocultures.
- Weathering of parent material is not a sufficient source of mineral elements, and obtaining adequate transfers of N from a grain legume to companion crops will be very difficult. Attempts to have perennial grain legumes release enough N to support a worthwhile crop of wheat will likely prove futile.
- Given the uncontrolled nature of polycultures, there is no assurance that a polyculture with greater N input will not be a source of nitrate pollution.

**Conclusions**

The vision of a highly productive perennial grain system is intriguing, but it is time to lay speculation aside. The Land Institute’s program urgently needs to make progress with perennial grains or their vision will remain a ‘pipe’ dream. In my view, there is only a remote possibility that a manageable perennial polyculture with grain yields and stability equivalent to those of annual monocultures can be achieved, and that grain legumes can supply the needed N. The outlook for supply of sufficient P and K by weathering of parent material is nil. Perhaps the Institute’s many Fellows now doing graduate research at leading universities will advance the work rapidly and prove me wrong. I look forward to learning of their results.
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