Natural Farming Systems: Meeting the Goals of Sustainable Agriculture

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Goals of Sustainable Agriculture

High productivity is a goal of all agricultural systems. This means efficient use of resources for optimal output to serve a variety of personal, social and economic needs. It almost never means “maximum” yields. All of this must be done with socially- and politically-acceptable environmental disruption. All agriculture, by definition, creates some degree of environmental disturbance. Agricultural systems purposefully disrupt natural systems, in an ecological sense, through patterns of human intervention. The disruption must increasingly be limited to fields and to upper soil layers where crops and animals are produced. This means that production materials (pesticides, nutrients, crop and animal residues, soil) must either be contained, or not used. Damage caused by insect pests and disease cycles must be held below economic threshold levels. Optimizing biological balance to minimize pesticide reliance is a requisite strategy. The management of weeds must move toward greater biological balance. An exciting new concept in weed management emphasizes managing the crop-associated plant community to provide added value toward production goals while not reducing crop yields.

High productivity, by definition, means achieving a high flow of nutrients through the loop from soil to crops, and in many cases, through animals and back to the soil. Inputs and out-puts to this high-flow loop occur through various economic pathways. Losses through dilution to the surrounding environment must be minimized.

To meet the plethora of family, community, regional and global needs for both economic well-being and quality of life, a diversity of farm and enterprise types is needed. The requirements for efficiency, for product containment and for appropriate environmental and human interface with agriculture must then apply across tremendous farm diversity. Our challenge is to identify basic concepts or principles for structuring of farming systems to achieve a multiplicity of goals, all within the constraints of sustainability.

Diversity of Farm Type as a Requisite for Sustainability

Agriculture within a community or a region, in order to remain viable, must maintain a sufficient magnitude to support the needed service industries and to elicit community support. This seems to be best accomplished by a mixture of farm types which not only achieve optimal use of the land resources, but also respond to local, regional and perhaps global market opportunities and needs, all of which make up the complex environmental matrix within which farms operate. Each farm type fits a niche within this matrix. The appropriate mix of farms in a region will vary with environment. Appropriate mixes in Vermont, Michigan, Iowa, Germany and Thailand all differ markedly, and they will evolve over time as social and economic conditions change. We will illustrate with a Michigan example.

Michigan agriculture, as it evolves toward sustainability, is changing on multiple fronts, and it is responding to changing markets, environmental standards and social expectations. Farm organization and patterns of production can be grouped into types, with characteristics defined by the paradigm (or pattern) chosen by farm managers.

The five farm system types discussed here have been gleaned from the current literature and grouped according to the organizational paradigm. Michigan agriculture is comprised of a mixture of those types. The types differ in their levels of biological integration and of community interactions, both social and economic. The pattern types merge into each other, but have commonly accepted identities.

Industrial Farms

These are typically large-scale, sometimes vertically-integrated enterprises with huge capital investments and farmed on an extremely extensive scale. They have few crops or separate production enterprises. Inputs dominate or control the biology of the system. These farms are the outgrowth of the 1960's through 1980's of farm expansion for large-scale efficiency. They produce huge volumes of products for national and global markets, usually at reasonably low cost. Capital investments in machinery and chemicals replace labor wherever possible. Such farms are often criticized for their adverse environmental and social impacts. Scientific efforts to lower their environmental impact revolve around fine-tuning of inputs, and in the future perhaps through "site-specific" management. They contribute to low market-cost protein and carbohydrate production.

Future Industrial Farms

A vision for the evolution of a portion of the industrial farm segment toward what might be called a specialty business model has been patterned exclusively after an industrial enterprise (Urban, 1991). These farms would produce identity-preserved, high-quality products for national and global markets. At least a portion of such a market segment is seen to be of high quality with low to zero chemical inputs to meet market demand (Urban, 1991).

Biologically Integrated Systems

Under pressure for greater efficiency of production and reduction of cost, and for reduction of environmental loading, many producers are moving toward (or enhancing) the biological integration of their systems. Use of crop rotations, cover crops, integrated pest management, landscape diversity and a host of other practices contribute to these goals (Harwood, 1985; Edwards, 1990). In Michigan, we are developing a strong ecological base for these integrative directions. The principles of ecological interaction include soil-based, landscape-1evel, and crop and animal species interaction types of relationships. This approach includes the fine-tuning (selection, timing, amounts, method of application, etc.) of inputs combined with the "structuring" of biological integration. "Integration" is translated into specific rotations, cover crops, animal grazing, and landscape-diversity types of practices. Community interaction must be, at a minimum, that of understanding and acceptance.

Sustainable Agriculture

The most current, and broad concept of sustainable agriculture is one that includes a significant element of "quality of life" (Flora, 1990; Ikerd, 1993). This concept was articulated in 1993 by a national committee appointed to define an approach toward implementation of the 1990 farm bill mandate. As stated, the quality of life concept includes emphasis on personal interaction at the family and particularly at the community level. The broad concept of sustainable agriculture seems to include not only biological integration but also major elements of community interaction through markets, flow of goods and services, support of local institutions and of local community empowerment and interaction. In a sense, it is a "value-added" approach at the community level, enhancing the non-economic as well as the economic value to the community of local agriculture. This concept of agriculture serves a broad range of needs at the local level and is highly important to the quality of life.

Holistic Agriculture

Holistic agriculture describes that portion of agriculture as defined by Wendell Berry, Wes Jackson and others. The integrative values of the biologically - and socially - integrated types are taken to greater extremes, to the point that a land ethic and a social ethic become the driving forces. Berry's "a sense of place" overrides most other considerations. Family and community are the key determinants of ultimate success.

State Agriculture as a Composite

All of the above farm paradigm types can be found in the State of Michigan. These occur because of different land types which permit or discourage large holdings; capital investment strategies and opportunities; market structures and opportunities; the presence of urban and rural markets; differences in environmental fragility; and a broad range of social, political and regulatory factors.

One could make a strong argument that agricultural sustainability at a statewide level is significantly enhanced by an appropriate balance of these types, each responding to different conditions and needs. The balance (in terms of acreage, total value or other indicators) changes with land type, and with proximity to communities and urban areas. The balance is (and should be) quite different in Vermont than it is in Michigan or Iowa. It changes over time. In Michigan we are evolving rapidly, for a variety of reasons, toward biological integration. Also, there are strong forces that compel movement toward social integration, but directions here are less clear.

The relationships between environmental sensitivity and protection, and community concerns involve increasing specialty market opportunities, pressure for community integration, and the quality of life. In the agriculture of developing countries, the same mix of farms with respect to the level of integration can be found (Harwood, 1994). However, a much broader range of system types is possible with high density human populations, where the number of people involved in agriculture can range from just a few to several hundred per square kilometer.

In discussions of sustainability, we must not confuse the issues of farm type and internal structure. Farms having a diversity of enterprises may or may not have appropriate spatial and temporal patterns of diversity to meet local sustainability goals. A11, however, must achieve a level of biological and social integration appropriate to the sensitivities of their 10cal environment.

Focal Points for Systems Integration

The need for efficiency of resource use, for response to markets, materials containment, management of pest levels, and a host of other factors, determines the structure within a farm type. Farmers respond to the challenges of integration by changing factors influencing various focal points of convergence within the systems. These focal points may include:

- ecology of pest/predator balance,
- species shift within the crop-associated plant community,
- nutrient flow over space and fluxes over time, and
- labor and machinery use profiles.

Some “tools” for integration include: use of rotations and cover crops, and use of both industrial and biological inputs.

Sustainability problems (imbalances) differ with the type of system and its environment. In some cases, pest management may dominate as a system integrator. In other cases the primary integrator may be nutrient flow management. In some, such as with potato production on an irrigated, sandy soil, both pest management and nutrient containment are foci for integration. These focal points are nearly always interrelated. While the “dominant” factor for integration may change, it might be useful to consider a hierarchy of relation-ships as follows:

- management of the soil biota (for soil quality and for nutrient flow),
- management of the crop-associated plant community, and
- management of pest/disease dynamics.

Managing the soil biota appears to be somewhat more generic than each of the others. The general principles can be used to structure systems across a wide range of environments and crop types. Systems structure for managing the soil biota having more general requirements provides a framework within which weeds, pathogens and pests may be managed.

Management of the Soil Biota

The mobilization and containment of nutrients in the soil at high flow rates between the soil and crop are basic requirements for sustainability. Regardless of the source of nutrient inputs, they depend on managing seasonal fluxes in the soil in synchrony with crop growth requirements and seasonal leaching cycles. Manipulation of those fluxes solely by input of nutrients in mineral form may satisfy a long-term input/output balance, but it will not necessarily result in the synchrony of availability/demand required for tightening the nutrient flow loops. Fluxes within the soil are highly influenced by the soil biota, and particularly by the microflora. The soil biota, in addition, influence many soil processes critical to soil quality and crop productivity (Table 1). Total biomass of the soil biota constitutes a relatively small fraction (one to eight percent) of the total soil organic matter. Hendrix et al. (1990) suggested that the relative amounts of organic matter in soil contributed by various sources could be approximated as: humus (n x 1000), living and dead vegetation (n x 100), microorganisms (n x 10) and soil fauna (n x 1). The biotic community is complex, and very unevenly distributed within the soil. The root surface-rhizosphere region contains a high proportion of microorganisms (Table 2).

Table1: Soil Biota as Components of Sustainable Agroecosystems.

Soil Biota	Influences of Sil Biota on Soil Processes in Ecosystems	
	Nutrient Cycling	Soil Structure
Microflora	Catabolize organic matter Mineralize and immobilize nutrients	Produce organic compounds that bind aggregates Hyphae entangle particles onto aggregates
Microfauna	Regulate bacterial and fungal populations Alter nutrient turnover	May affect aggregate structure through interactions with microflora
Mesofauna	Regulate fungal and microfaunal populations Alter nutrient turnover Fragment plant residues	Produce fecal pellets Create biopores Promote humification
Macrofauna	Fragment plant residues Stimulate microbial activity	Mix organic and mineral particles Redistribute organic matter and microorganisms Create biopores Promote humification Produce fecal pellets

From: Hendrix et al., 1990.

Table 2: Comparison of the Numbers of Various Groups of Organisms in the Rhizosphere of Spring Wheat and in Control Soil

Organisms	Numbers per g in Rhizosphere Soil (x 10^{-6})	Numbers per g in Control Soil (x 10^{-6})	Approximate Rhizosphere: Soil Ratio
Bacteria	1,200	53	23:1
Actinomycetes	46	7	7:1
Fungi	12	0.1	120:1
Protozoa	0.0024	0.001	2:1
Algae	0.005	0.027	0.2:1
Bacterial Groups			
Ammonifiers	500	0.04	12,500:1
Gas-producing anaerobes	0.39	0.03	13:1
Anaerobes	12	6	2:1
Denitrifiers	126	0.1	1,260:1
Aerobic cellulose decomposers	0.7	0.1	7:1
Anaerobic cellulose decomposers	0.009	0.003	3:1
Spore formers	0.930	0.575	2:1
“Radiobacter” types	17	0.01	1,700:1
Aztobacter	< 0.001	< 0.001	?

Adapted from: T.R.G. Gray and S.T. Williams. 1975. Soil Microorganisms, Longman, New York. P. 144. In: National Research Council, 1979.

The management and use of soil biota in agriculture has been heavily discounted for the past several decades. Various attitudes toward introduction of beneficial microorganisms to soil can be summarized as follows. "Present evidence is insufficient to justify the use of inoculants, other than rhizobia for legumes, to increase crop yields, improve plant quality, or control disease" (National Research Council, 1979). In stark contrast to this is the conclusion of a keynote speaker at the 1994 15th World Congress of Soil Science, i.e., that "inoculation of soils with microorganisms is a powerful methodology for manipulation of the soil ecosystem" (van Veen and Heijnen, 1994). Other authors (Silver et al., 1986) have stated: "The most important chemical changes (in the soil) include the solubilization of nutrient ions such as phosphate, sulfate, K, Fe, Ca, Zn, Mg, Co and Mn, thus increasing their availability to the soil biota… With increasing research in this area, microbes have been found to be the essential agents causing these transformations."

The greater use of technologies to biologically manage soil fertility was recently described by Sanchez (1994) to constitute a "second paradigm" in soil fertility management (the first paradigm being that of industrial fertilizer use). The second paradigm, which has emerged, states: "Rely more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity, and optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use." The key to this paradigm is to identify and understand those factors which influence soil biological activity and which can be managed by the farmer.

Soil physical properties have a significant effect on the sequestering of carbon and providing a favorable habitat for microorganisms. This determining micro-structure, however, is a result of parent material and the soil formation process, and is not subject to management. Soil moisture is a very important and critical factor in biotic activity. Soil chemistry, particularly pH, does play a role. Within the chemical range for optimal plant growth, substrate (carbon source materials) is the prime determinant of species diversity, population level and activity of soil biota (van Veen and Heijnen, 1994). Substrate quality, including lignin content and C/N ratio are important and can be manipulated advantageously to enhance soil quality through the timeliness and precision of farm operations.

Managing the Soil Biota Through Control of Substrate

Selection of crops, controlling the period of active growth to maximize rhizophere activity, and use of introduced microorganisms, are three ways of managing the soil biota. The latter factor is well covered by other papers in this conference. The approach at Michigan State University has been to manipulate the soil biota by managing soil substrate levels. This is an approach that has been utilized by researchers in the Tropical Soil Biology and Fertility Program (Swift, 1994).

The distribution of carbon sources in soil is highly variable. However, the root surface-rhizosphere region provides an abundance of organic and inorganic nutrients, growth factors and a most favorable microenvironment that can support a high level of microbiological activity (Table 2). Some authors go so far as to claim that "the bulk of non-rhizophere soil is oligotrophic, in essence a nutritional desert" (Metting, 1993). This rhizosphere-centered view of the soil is not uncommon. Scientists who focus on the role of mycorrhizae in disease suppression, nutrient flow and soil aggregation share this view (Bethlenfalvay, 1994; Linderman, 1994; Tisdall, 1994).

In research at Michigan State University, we are attempting to measure overall soil biota levels by multiple samples that are designed to sample across microsite variability. Soil samples at standard depth increments were taken to assess the root biomass patterns. Microbial biomass is used as a primary indicator of biological activity. The greatest microbial differences are nearly always found in the upper 30 cm of soil. In the long-term Rodale Farming Systems Trial, Harris (1993) found that after ten years the high crop diversity-organic rotation had significantly greater microbial biomass compared with a conventional corn-soybean rotation (Table 3). No manure or biological inoculum had been used in these treatments. Nitrogen mineralization potential in the diverse rotation was double that of the corn-soybeans. Total organic matter levels were the same in both treatments, indicating that a higher portion of the organic matter was represented by microbial populations in the diverse rotation (3.4 percent as compared with 2.0 percent).

Table 3: Soil Microbial Biomass and Mineralization Potential after Ten Years in Corn Plots of the Rodale Long-Term Farming Systems Trial.

Biomass Component	Diverse Rotation[1]	Corn-Soybean Rotation[2]
N mineralization (g/g)	11.6	5.4
Biomass N (ug/g)	186	86
Biomass N : soil N ratio	.052	.030
Biomass C (ug/g)	758	403
Biomass C/soil C	.034	.020

Source: Harris, 1993

[1] Diverse rotation: no chemical used.

1981	oats/red clover	1985	soybean	1989	wheat/red clover
1982	corn	1986	oats/red clover	1990	corn
1983	oats/red clover	1987	corn	1991	soybean/wheat
1984	corn	1988	soybean/wheat	1992	wheat/hairy vetch

[2] Corn-soybean rotation: alternate years; chemical fertilizer, herbicides used

Total plant dry matter production was higher in the corn-soybean rotation, so the diverse, organic rotation had increased in microbial biomass while receiving lower carbon input. The corn-soybean rotation had living crops in the field approximately 40 percent of the time as compared with more than 80 percent for the diverse rotation. It is not known whether the increase is due to greater diversity of substrate, longer duration and greater volume of root rhizophere activity, the absence of chemical inputs, or a combination of the three.

After 4.5 years in the Long-Term Ecological Research (LTER) plots at Michigan State University, a conventionally-farmed, corn-soybean rotation had 313 µg/g of soil microbial biomass carbon, whereas a complex, no chemical input rotation had 405 µg/g, a 6-year old native succession 422 µg/g, and an 80-year-old native grassland 475 µg/g. Here, again, with lower carbon inputs, the proportion of microbial biomass carbon in the total soil carbon pool increased with crop diversity, the amount of root rhizosphere, and the time or duration of the treatment (Paul et al., 1993). Carbon mineralization potentials followed a similar pattern of increase.

These results have led to the following working hypotheses within the LTER experiment: "The active fraction of the soil organic matter, which provides the majority of non-fertilizer-derived crop nitrogen, is maintained primarily by interactions among litter quality and soil microbial-invertebrate activity. Communities with greater soil organic matter reserves, and with greater proportions of active fractions and. aggregate stabilities (resulting from long-term land use patterns), are better buffered from the effects of short-term disturbance."

Ongoing research is designed to further clarify the causal effects and biological processes contributing to these differences. The Living Field Laboratory, a factorial experiment adjacent to the LTER at the Kellogg Biological Station in Michigan, is designed, in particular, to separate crop species diversity from organic vs. chemical management. Treatments, all with chisel plowing, range from six-crop and cover crop species in four years with compost and no chemicals to continuous corn with full chemicals, including most of the intermediate combinations.

Conclusions for Sustainable Farming Systems Management

It seems apparent that for a region's agriculture to be sustainable it must have a diversity of farm types to appropriately utilize the diverse production resources as well as to serve its many markets and meet social and political expectations. The range of farm types and their relative frequency differs with population density and a host of other environmental factors. A pattern of crop and animal diversity across the landscape is of significant benefit in managing pest-predator relationships as well.

It is very important, for purposes of achieving a reasonable degree of biological balance and efficiency of nutrient flow, to have an appropriate level of crop diversity in each farm system. Cover crops can complement but not completely replace crop diversity. It is suggested here that structuring crop diversity over time for purposes of increasing soil biotic activity can serve as a basis for rotations that can then be adjusted for appropriate management of the crop-associated community and for pest management. These elements of biological integration will be essential for containment of production materials and for stabilizing yield in high productivity, sustainable farming systems.

References

Bethlenfalvay, G.J. 1994. Sustainability and rhizo-organisms in an agrosystem. p. 9-10. In 15th World Congress of Soil Science. Volume 4a: Symposium IIIa. Acapulco, Mexico.

Edwards, C.A. 1990. The importance of integration in sustainable agricultural systems. p. 249-264. In C.A. Edwards, R. Lal, R. Madden, R. Miller, and G. House (ed.) Sustainable Agricultural Systems. The Soil and Water Conservation Society, Ankeny, Iowa.

Flora, C.B. 1990. Sustainability of agriculture and rural communities. p. 343-359. In C.A. Francis, C.B. Flora, and L.D. King (ed.) Sustainable Agriculture in Temperate Zones. John Wiley & Sons, Inc., New York, N.Y.

Harris, G.H. 1993. Nitrogen cycling in animal-, legume-, and fertilizer-based cropping systems. Ph.D Dissertation. Michigan State University, East Lansing, Michigan. 172 p.

Harwood, R.R. 1985. The integration efficiencies of cropping systems. p. 64-75. In T.C. Edens, C. Fridgen, and S.L. Battenfield (ed.) Sustainable Agriculture and Integrated Farming Systems. Michigan State University Press, East Lansing, Michigan.

Harwood, R.R. 1994. Agronomic alternatives to slash and burn in the humid tropics. p. 93-106. In P.A. Sanchez and H. van Houten (ed.) Alternatives to Slash-and-Burn Agriculture. 15th World Congress of Soil Science. Symposium ID-6. Acapulco, Mexico.

Hendrix, P.F., D.A. Crossley, Jr., J.M. Blair, and D.C. Coleman. 1990. Soil biota as components of sustainable ecosystems. p. 637-654. In C.A. Edwards, R. Lal, R. Madden, R. Miller, and G. House (ed.) Sustainable Agricultural Systems. The Soil and Water Conservation Society, Ankeny, Iowa.

Ikerd, J.E. 1993. Sustainable agriculture: Farming in harmony with the biosphere. p. 12-23. In : L.A. Johnson (ed.) Sustainable Agriculture Enhancing the Environmental Quality of the Tennessee Valley Region Through Alternative Farming Practices. University of Tennessee, Knoxville, Tennessee.

Linderman. R.G. 1994. Biological control of root pathogens. p. 3-8. In 15th World Congress of Soil Science. Volume 4a: Symposium IIIa. Acapulco, Mexico.

Metting, F.B., Jr. 1993. Structure and physiological ecology of soil microbial communities. p. 17-21. In F.B. Metting (ed.) Soil Microbial Ecology: Applications in Agricultural and Environmental Management. Marcel Dekher, Inc. New York.

National Research Council. 1979. Soil microbes in plant health and nutrition. p. 48. In Microbial Processes: Promising Technologies for Developing Countries. National Academy of Sciences. Washington, D.C.

Paul, E., T. Willson, D. Harris, and E. Franco-Vizcaino. 1993. Soil microbial dynamics and carbon mineralization kinetics. In Report on Long-Term Ecological Research-All-Scientist Meeting, Estes Park, Colorado.

Sanchez, P.A. 1994. Tropical soil fertility research: Towards a second paradigm. p. 65-88. In 15th World Congress of Soil Science. Volume I: Inaugural and State of the Art Conferences. Acapulco, Mexico.

Silver, M., H.L. Ehrlich, and K.C. Ivarson. 1986. Soil mineral transformation mediated by soil microbes. p. 497-519. In P.M. Huang and M. Schnitzer (ed.) Interactions of Soil Minerals with Natural Organics and Microbes. SSSA Special Publication 17. Soil Science Society of America. Madison, Wisconsin.

Swift, M.J. 1994. Future prospects for biological management of soil fertility as a component of sustainable agriculture. p. 61. In 15th World Congress of Soil Science, Volume 4a:

Symposium IIIb. Acapulco, Mexico.
Tisdall, J. 1994. Mycorrhize and soil conservation. p. 11-12. In 15th World Congress of Soil Science. Volume 4a: Symposium IIIa. Acapulco, Mexico.
Urban, T.N. 1991. Agricultural industrialization: It's inevitable. Choices (Fourth Quarter). p. 4-6.
van Veen, J.A. and C.E. Heijnen. 1994. The fate and activity of micro-organisms introduced into soil. p. 47-64. In 15th World Congress of Soil Science. Volume 1: Inaugural and State of the Art Conferences. Acapulco, Mexico.