PUNTO DE VISTA - VIEWPOINT

ELEMENTS OF SUSTAINABLE AGRICULTURE†

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ABSTRACT

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A nearly infinite number of dimensions must be considered if productivity of an agroecosystem is to be sustained indefinitely. In many cases, the most limiting element may determine the future sustainability of the system and set the context in which management decisions, including those involving nematodes, must be made. Some examples of critical elements that may change over time include human population size, water, fossil fuel energy, nitrogen, carbon dioxide, salinity, economics, and amount of cropland. The implications of these factors in future nematode management strategies are discussed briefly. The multiple dimensions affecting the sustainability of an agroecosystem parallel the dimensions of the ecological niches of the organisms involved, but include a number of human-imposed dimensions (political, social, economic, and management practices) as well. A variety of complex problems, some with conflicting solutions, must be addressed in the planning and design of agroecosystems sustainable for future generations.

Key words: agroecosystem, ecological niche, nematode, nematode management, sustainability, sustainable agriculture.

RESUMEN

McSorley, R., and D. L. Porazinska. 2001. Elementos de la agricultura sustentable. Nematrópica 31:1-9.

Un número casi infinito de medidas deben ser consideradas para que la productividad de un agroecosistema se sostenga idefinidamente. En muchos casos, el elemento más limitante puede determinar la futura sustentabilidad del sistema y establecer el contexto en el cual se deben tomar decisiones sobre manejo incluyedo aquellas relacionadas con nematodos. Entre algunos ejemplos de elementos criticos que pudieran cambiar a través del tiempo se encuentran: población humana, agua, energia procedente de combustible fósil, nitrógeno, dioxido de carbono, salinidad, economía y cantidad de tierra agrícola. Las implicaciones de estos factores en el futuro de las estrategias para el control de nematodos se discuten brevemente. Las multiples dimensiones que afectan la sustentabilidad de un agroecosistema van paralelas a las dimensiones de los nichos ecológicos de los organismos que forman parte de él, también incluyen un número de medidas impuestas por el hombre (politica, social, económica, y practicas de manejo). Una variedad de problemas complejos, algunos con soluciones conflictivas que deben ser considerados en la planificación y diseño de agroecosistemas sustentables para las generaciones futuras.

Palabras claves: Agricultura sustentable, agroecosistema, manejo de nematodo, nicho ecológico, nematodo, sustentabilidad.

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INTRODUCTION

Although much emphasis has been given to sustainable agriculture over the last decade, the term has been variously defined (Benbrook, 1990; 1991; Crews *et al.*, 1991; Parr, 1991; Powers and McSorley, 2000). Most current definitions emphasize maintenance of ecosystem productivity and an adequate food supply for all people, preservation of environmental quality, and conservation of nonrenewable resources and biological diversity. Food safety, economic, and social components are often included. A time element is fundamental to the concept of sustainability, due to the dynamic nature of agroecosystems, and the most credible systems are those which are intergenerational or maintained for an even longer time period (Christensen *et al.*, 1996; Ellis and Wang, 1997). Systems cease to be sustainable when a resource is depleted, when unacceptable levels of pollution or other environmental problems occur, or when practices to maintain them are no longer economically or socially acceptable.

While a sustainable agroecosystem is a desirable goal, achieving this ideal can be difficult, since so many elements affect the function and integrity of agroecosystems. A few of the more critical elements with potential to affect many agroecosystems are discussed below. Central to all sustainable systems is the issue of time. Sustainability is not a one-year, two-year, or short-term goal; success is measured over generations or even centuries. However, even within the next few decades, several critical elements may show important changes that may have possible implications in agriculture and therefore in nematode management.

SOME CRITICAL ELEMENTS OF SUSTAINABILITY

World Population. The human population has been growing at an exponential pace, passing 4 billion in the mid-1970s and 6 billion in 1999. Various forecasts project a population size of about 8.5 billion in 2025 (Powers and McSorley, 2000; Spedding, 1996; World Resources Institute, 1994). A population size of 8 billion represents an increase of 33% over the 6 billion present in 1999, and therefore should demand a corresponding 33% increase in food supply over current levels. Note that sustainability does not imply maintenance of present-day production levels. For food supply per capita to remain level, projected population increases over the next two decades require that agricultural production must increase greatly or distribution of food must greatly improve.

One method of increasing production is by limiting losses to nematodes, insects, weeds, and plant pathogens. A world survey (Sasser and Freckman, 1987) estimated annual losses of 10.7% to nematodes on 20 life-sustaining crops. Recent estimates (Koenning et al., 1999) of losses to nematodes in the United States are somewhat lower (<5% on most crops) but still represent a substantial amount of production.

CO_2 and Temperature. The annual increases in atmospheric CO_2 concentrations have been well documented since the late 1950s (Keeling and Whorf, 1994). Trends in temperature increases anticipated from global warming are less clear, with an increase of 0.5°C reported during the 30 years prior to 1993 (Wilson and Hansen, 1994). The warmest years of the 20th century occurred during its last two decades (Brown, 1997).

Temperature increases of 1.0°C or 2.75°C would have predictable effects in shortening the life cycles of nematodes such as *Meloidogyne incognita* (Table 1). Under these scenarios, a temperature increase of 2.75°C would reduce the generation time by 15% (assuming 25°C initial temperature) to 22% (assuming 20°C ini-

Table 1. Time required for *Meloidogyne incognita* to reach second generation[y] under various temperature change scenarios, based on initial temperatures of 20°C or 25°C.

	Time (days)	
Temperature change	20°C initial temperature	25°C initial temperature
0°C	50.0[z]	33.3
+1.0°C	45.4	31.2
+2.75°C	39.2	28.2

[y]Second-stage juvenile to second-stage juvenile.
[z]Assume 500 degree days (above 10°C base) for complete generation, based on data from Sydenham *et al.* (1997) for *M. incognita* on 'Black Valentine' bean.

tial temperature). Such changes would result in more generations per year as well as more rapid development to reproductive stages. Increases in mean temperatures could also be expected to result in changes in the geographic ranges of some plant-parasitic nematodes and their hosts. In the Northern Hemisphere, the ranges of species like *M. incognita* or *Radopholus similis* may expand northward, while ranges of nematodes preferring cooler climates (e.g., *M. hapla, Globodera pallida*) might contract. Based on proposed distribution maps for root-knot nematodes (Taylor and Sasser, 1978), an increase of 2.75°C would be predicted to result in a northward shift of about 150 km for *M. incognita* and *M. javanica* in the eastern United States. In addition to the increased potential for nematode damage resulting from range changes or more rapid generation times, higher temperatures may reduce the expression of nematode resistance in some crops (Dropkin, 1969; Sydenham *et al.*, 1997). Increased potential for nematode damage may be partially offset by increased plant growth rates and increased activity of nematode antagonists. A major concern is that climate change may lead to disruption of weather and temperature patterns, leading to problems in crop production as well (Brown, 1997).

In addition, temperature change may alter activity rates of nematodes and other organisms involved in the decomposition process, increasing decomposition rates and the availability of nutrients from organic sources. Carbon sequestration is proposed as a strategy for moving some of the atmospheric CO_2 into crop biomass and soil organic matter (Lal *et al.*, 1999). If this strategy is pursued, the increased soil organic matter could be expected to stimulate soil food webs. Because of such trends, future changes in soil organic matter and soil food webs are difficult to anticipate; organic matter may increase from carbon sequestration, but its removal may be accelerated by increased decomposition rates.

Water. The amount of land under irrigation has increased greatly during the second half of the 20th century (Brown, 1997). Agricultural demands for irrigation water have resulted in lowering of water tables, reduction in flow of rivers, reduction of size in lakes and ponds, and other supply problems (Brown, 1997; Powers and McSorley, 2000). Conservation of the freshwater supply is essential for a sustainable agricultural system, and will likely require a variety of practices such as recycling of water, efficient irrigation practices, optimum timing of irrigation, mulches, conservation tillage, and optimum management of watersheds and recharge areas. Nematodes, particularly those infecting roots, can further increase water stress on plants (Wilcox-Lee and Loria, 1987). On the other hand, use of mulches or other practices that retain soil moisture may help improve crop tolerance to nematodes (McSorley and Gallaher, 1995). Conservation tillage, while important for erosion and water management, does not appear to impact plant-parasitic nematodes in a consistent manner (McSorley, 1998; Minton, 1986). Conservation tillage and other practices that conserve or add soil organic matter may stimulate certain groups of nematodes involved in decomposition (Fu *et al.*, 2000).

Fossil Fuels. Petroleum, coal, and natural gas are finite resources subject to depletion. Although petroleum consumption has escalated in recent decades, new discoveries have kept reserves constant at a 40-50 year supply (World Resources Institute, 1996). However, assuming that a 33% increase in world population corresponds to a 33% increase in petroleum consumption, a 50-year petroleum reserve would become a 37.5-year reserve. An increase in the per capita consumption of petroleum or a failure in the ability of new discoveries to keep pace with consumption would lead to a more rapid depletion of known reserves. Limitations in availability of petroleum and other fossil fuels would increase cost or limit many nematicides, insecticides, herbicides, fungicides, or fertilizers that are derived from fossil fuels or require energy from fossil fuels for their production or for their application.

Energy. Currently, much of the energy input to agricultural systems is derived from fossil fuels. The production of many systems increases with the amount of energy supplied (Pimentel and Dazhong, 1990; Powers and McSorley, 2000; Tivy, 1992). However, the efficiency of agricultural production tends to decrease as energy inputs increase. For instance, corn yield in the United States in 1980 was nearly 3.5 times that in 1920, when energy input was only 12.5% of the 1980 level (Pimentel and Dazhong, 1990). While there was a great increase in overall production during that 60-year period, it was accompanied by a decrease in the efficiency of energy use. One of the greatest challenges in establishing sustainable systems is to maintain current high production levels while increasing energy use efficiency and using less energy or renewable energy sources.

Nitrogen. In many agricultural systems, the greatest single energy input is for synthetic nitrogen fertilizers (Pimentel and Burgess, 1980). The high energy required for manufacture of synthetic fertilizers is currently obtained from fossil fuels, so any future limitations in fossil fuels would affect synthetic fertilizers as well. Under such scenarios, nitrogen conservation is essential, with increased emphasis on recycling of nitrogen and reduction of losses, and on the use of organic amendments and nitrogen fixation by legumes and green manures as primary nitrogen sources.

Overall, the effect of organic amendments on plant-parasitic nematodes is variable and inconsistent, but some materials may have potential in this area (McSorley, 1998; McSorley and Duncan, 1995; Muller and Gooch, 1982; Rodriguez-Kabana, 1986; Stirling, 1991). Many of them help to improve plant performance, regardless of their effects on nematodes. Widespread planting and use of legumes may be required to meet future nitrogen demands. However, research is needed to maximize the efficiency of previous legume cover crops or legume hays in meeting nitrogen needs of subsequent crops in cropping systems (Giller and Wilson, 1991; Peoples *et al.*, 1995; Power 1990; Powers and McSorley, 2000). Whether or not the inclusion of more legumes in cropping systems would increase nematode problems depends on the nematodes and cropping systems involved. In the southeastern United States, *Meloidogyne* spp. often build up more readily on legumes than on non-legume cover crops, and so nematode-resistant legumes may be particularly desirable for such systems (McSorley, 1999; Weaver *et al.*, 1993, 1998).

Economics. For a practice to be sustainable, it must be adopted and used by growers. Economics often provides the incentive for adoption. In some cases, economic goals may conflict with other elements of sustainability, as for example, if a practice useful for conservation of water or nutrients is not profitable for a farmer (Porazinska *et al.*, 1998). Availability of inexpensive synthetic nitrogen fertilizers is the main reason that they are currently preferred over organic fertilizers, and their use is actually increasing for this reason (Robertson, 1997). This is in direct conflict with the nitrogen and energy conservation issues mentioned in previous sections, but illustrates the overriding importance of economics as a component of sustainability.

For a number of years, it has been recognized that the use of methyl bromide for nematode management is not sustainable due to environmental concerns and regulation (McSorley *et al.*, 1985; Noling and Becker, 1994). Yet in many systems, nematicides derived from fossil fuels are preferred over non-chemical alternatives because of their efficacy and profitability. Non-chemical alternatives will be acceptable if effective and profitable (Chellemi *et al.*, 1997), and so an important challenge is to improve the efficacy and profitability of sustainable methods for nematode management.

Pollutants and Contaminants. Systems are not sustainable if hazardous materials are produced or accumulated over time. These may include objectionable concentrations of heavy metals, pesticide residues or other toxic chemicals, fertilizer elements, or other materials applied in excess, although historically salts have probably been the most destructive contaminants of agricultural land. Salinization, a problem since ancient times, continues to render land unsuitable for production at a rate of about 1.5-2.5 million ha per year, largely a result of poor irrigation practices (Gardner, 1997). Effects of salt and other contaminants on nematodes vary. For example, salinity decreased population densities of *Rotylenchulus reniformis* (Heald and Heilman, 1971) but stimulated *Tylenchulus semipenetrans* under some conditions (Mashela *et al.*, 1992).

Cropland. If the world supply of cropland remained constant, the 0.25 ha per person available to the 6 billion people today would decline to 0.19 ha per person with a population of 8 billion (Powers and McSorley, 2000). Globally, cropland is expanding slightly, with losses from erosion, urbanization, and salinization more than offset by conversion of forests, other natural areas, and grasslands (World Resources Institute, 1996). Habitat destruction is the main reason for loss of biodiversity (Collins and Qualset, 1999), and negative effects apply to soil ecosystems as well (Neher and Barbercheck, 1999). However, fewer problems with plant-parasitic nematodes may be expected on new land than on land cropped continuously to food crops. Likewise, if pasture land is converted to food crops, problems with some plant-parasitic nematodes may be limited if the pasture grass was a poor host. For example, it is known that some pasture grasses, such as bahiagrass (*Paspalum notatum*), are favorable rotation crops for managing *Meloidogyne* spp. and *Heterodera glycines* (Weaver *et al.*, 1998).

ECOLOGICAL NICHE THEORY AND SUSTAINABILITY

An agroecosystem requires many different resource inputs that may result in many potential environmental impacts. When present in excessive or insufficient amounts, any of these inputs or outputs has the potential to render a system unsustainable. There is a useful parallel between the components of agricultural sustainability and those included in the concept of the ecological niche. In a most general sense, the ecological niche refers to all of those factors that affect the occurrence of an organism in a particular place (Begon *et al.*, 1990; Odum, 1983). Because these factors are so numerous, the *n*-dimensional nature (where *n* approaches infinity) of the niche was recognized (Hutchinson, 1957).

Similarly, the components of agricultural sustainability have *n* dimensions. These include physical resources such as water, light, land, or various nutrients, which must be maintained at sufficient levels to sustain a system. As with physical niche dimensions in ecology (Begon *et al.*, 1990; Hutchinson, 1957), inadequate or excessive levels of these elements would limit the sustainability of a system (Fig. 1). Excessive levels of pollutants may be particularly limiting. But the *n* dimensions of agricultural sustainability encompass much more than these physical factors. Some dimensions of sustainable agriculture are biological, such as population levels of a non-target species (e.g., a beneficial insect, free-living nematodes), or numbers of species (biodiversity) in a region. Economic, political, and social dimensions may be included as well. Regardless of the magnitude of *n*, the great number of potential interactions among so many factors limits our ability to predict an outcome based on information about individual factors obtained under controlled conditions.

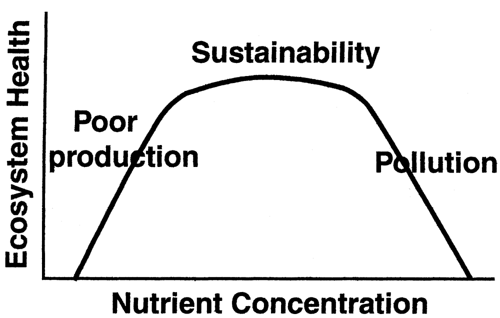

Fig. 1. Relationship between ecosystem health and nutrient concentration, for a nutrient showing a relatively normal distribution. An optimum nutrient concentration exists for which sustainability of the system is possible. If the nutrient level is inadequate, production will be insufficient to sustain the system, while if the level is excessive, pollution may affect ecosystem quality.

In ecological niche theory, the niche dimension that is most limiting will dictate the occurrence of an organism in a particular habitat. A similar law of the minimum applies to the sustainability of agroecosystems. Even if most dimensions are sufficient, an agroecosystem may become unsustainable if any one resource runs out or if the level of some negative dimension is reached or exceeded. Thus, defining sustainability is a difficult goal because all elements (*n* dimensions) must be considered, or the definition is limited! Operationally, it may be convenient and necessary to limit the definition, and therefore some of the more critical elements were emphasized here. But there is a possibility that some unmeasured dimension or interaction may eventually lead to an unsustainable system.

DEFINING A SUSTAINABLE SYSTEM

Due to the multitude of elements involved and potential conflicts among them, developing, or even defining, a sustainable agroecosystem is not a simple task. Much detailed specific information is needed for the planning of sustainable systems. All agroecosystems are different, so further clarification of objectives and definition of measurable tolerance limits are needed to define a specific sustainable system. Clear answers to the following questions are required:

What is to be sustained? (People, endangered species, specific resources, a specific level of production, a particular lifestyle, or all of these?)

At what level? (Population size, desired resource level, how many species?)

For how long? (One season, five years, a generation, 100 years?)

What is the size and location of the system? (A single field, a farm, a region, a country, the world?)

What are the limits of each dimension? (Desirable levels of each dimension, measurable definitions of pollution?)

How does the system fit into the landscape? (Interactions with other ecosystems, fate of inputs and outputs?)

Much research will be needed to define the limits of the various dimensions and to develop practices that maintain them. In addition, the dynamic nature of the agroecosystem and changes in dimensions over a long time scale must always be considered. Economic factors and social trends are particularly subject to market and temporal fluctuations, and there is some question about whether those should be included as components of sustainability (Crews *et al.*, 1991). When economic dimensions are included, it is critical that they reflect real and long-term values, not short-term profits resulting from legislation, subsidies, or temporary oversupply (Duncan and Noling, 1998). Even though environmental sustainability is a prerequisite for social and economic sustainability (Goodland and Daly, 1996), realistic and accurate economic and social dimensions should be included in agricultural sustainability because exclusion of these factors may result in an unrealistic system that will not be adopted or sustained.

Definition and design of sustainable agroecosystems are difficult issues because of the many elements or dimensions involved. Also, no agroecosystem by itself is 100% sustainable since some harvested product is usually removed from the agroecosystem. Therefore, the sustainability of any agroecosystem is interdependent with that of urban and natural systems, and so true sustainability may not be possible except in a sustainable biosphere or universe. However, the recognition and definitions of the elements of sustainable agriculture can provide goals to aspire to or approach in developing "more sustainable" systems.

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