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Soil & Tillage Research 72 (2003) 203–211

Soil & Tillage Research

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Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems

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Received 5 March 2002; accepted 3 March 2003

Abstract

Cultural methods such as crop fertilization can affect susceptibility of plants to insect pests by altering plant tissue nutrient levels. Research shows that the ability of a crop plant to resist or tolerate insect pests and diseases is tied to optimal physical, chemical and mainly biological properties of soils. Soils with high organic matter and active soil biology generally exhibit good soil fertility. Crops grown in such soils generally exhibit lower abundance of several insect herbivores, reductions that may be attributed to a lower nitrogen content in organically farmed crops. On the other hand, farming practices, such as excessive use of inorganic fertilizers, can cause nutrient imbalances and lower pest resistance. More studies comparing pest populations on plants treated with synthetic versus organic fertilizers are needed. Understanding the underlying effects of why organic fertilization appears to improve plant health may lead us to new and better integrated pest management and integrated soil fertility management designs.

Keywords: Soil fertility; Crop nutrition; Pest attack; Insect populations; Pest management

1. Introduction

Many researchers have suggested that increasing insect pest and disease pressure in agroecosystems is due to changes that have occurred in agricultural practices since World War II. For example, the usage of fertilizers and pesticides has increased rapidly during this period and evidence suggests that such excessive use of agrochemicals in conjunction with expanding monocultures has exacerbated pest problems (Conway and Pretty, 1991). On the other hand, proponents of alternative agricultural methods contend that crop losses to insects and diseases are reduced with organic farming (Merrill, 1983; Oelhaf, 1978). Although this view is widespread, there have been surprisingly few attempts to test its validity. The few conducted studies suggest that lower pest pressure in organic systems could result from the greater use of crop rotation and/or preservation of beneficial insects in the absence of pesticides (Lampkin, 1990). Alternatively, reduced susceptibility to pests may be a reflection of differences in plant health, as mediated by soil fertility management (Phelan et al., 1995). Many researchers and also practicing farmers have observed that fertility practices that replenish and maintain high soil organic matter and that enhance the level and diversity of soil macro- and microbiota provide an environment that through various processes enhances plant health (McGuiness, 1993).

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0167-1987/03/$ – see front matter
doi:10.1016/S0167-1987(03)00089-8

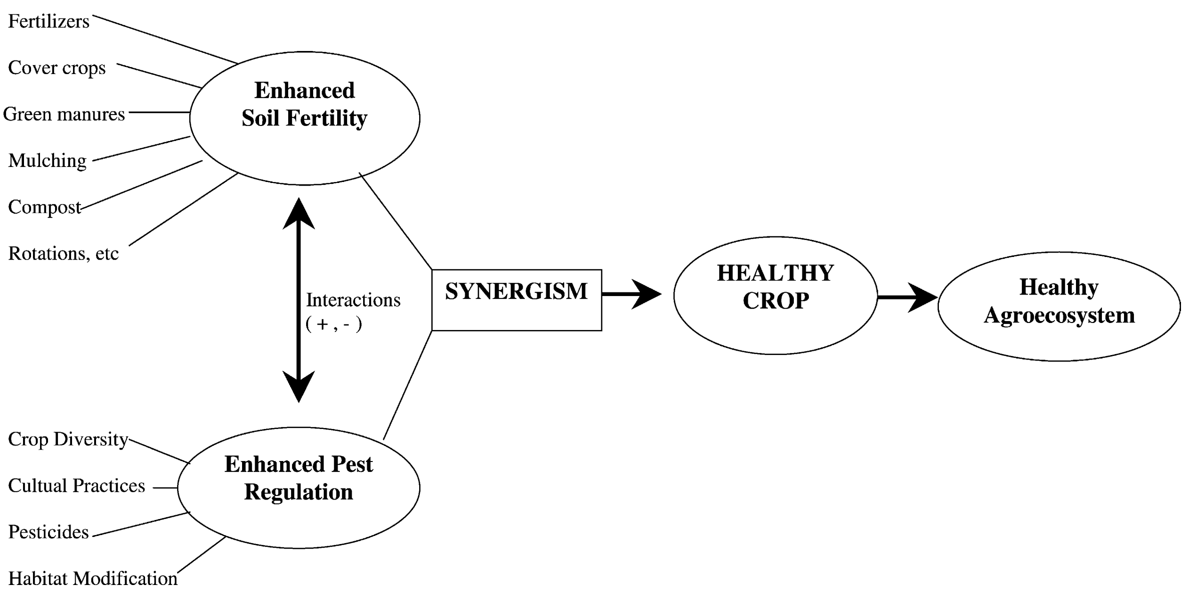

Fig. 1. The potential synergism between soil fertility management and IPM.

Despite the potential links between soil fertility and crop protection, the evolution of integrated pest management (IPM) and integrated soil fertility management (ISFM) have proceeded separately. The integrity of the agroecosystem relies on synergies of plant diversity and the continuing function of the soil microbial community, and its relationship with organic matter (Altieri and Nicholls, 1990). Most pest management methods used by farmers can be considered soil fertility management strategies and vice versa. There are positive interactions between soils and pests that once identified can provide guidelines for optimizing total agroecosystem function (Fig. 1). Increasingly, new research is showing that the ability of a crop plant to resist or tolerate insect pests and diseases is tied to optimal physical, chemical and mainly biological properties of soils. Soils with high organic matter and active soil biology generally exhibit good soil fertility as well as complex food webs and beneficial organisms that prevent infection. On the other hand, farming practices that cause nutrition imbalances can lower pest resistance (Magdoff and van Es, 2000).

Much of what we know today about the relationship between crop nutrition and pest incidence comes from studies comparing the effects of organic agricultural practices and modern conventional methods on specific pest populations. Soil fertility practices can impact the physiological susceptibility of crop plants to insect pests by either affecting the resistance of individual plant to attack or by altering plant acceptability to certain herbivores. Some studies have also documented how the shift from organic soil management to chemical fertilizers has increased the potential of certain insects and diseases to cause economic losses.

2. The effects of fertilization on plant resistance to insect pests

Studies of plant resistance to insect pests have shown that resistance varies with the age or growth stage of the plant (Slansky, 1990). This suggests that resistance is linked directly to the physiology of the plant and thus any factor that affects the physiology of the plant may lead to changes in resistance to insect pests.

Fertilization has been shown to affect all three categories of resistance proposed by Painter (1951): preference, antibiosis, and tolerance. The obvious morphological responses of crops to fertilizers, such as changes in growth rates, accelerated or delayed maturity, size of plant parts, and thickness and hardness of epicuticle, also influence the success of many pest species in utilizing the host. For example, Adkisson (1958) reported nearly three times as many boll weevil larvae (*Anthonomus grandis*) on cotton (*Gossypium hirsutum*) receiving heavy applications of fertilizers compared to unfertilized checks. He attributed these differences to the prolonged growing season for cotton resulting from the fertilizer amendment by which plants remain succulent longer and fruit later in the season than normal. Klostermeyer (1950) reported that nitrogen fertilizer increased husk extension and tightness of husks on sweet corn (*Zea mays*) influencing corn earworm (*Heliothis zea*) infestation levels.

Meyer (2000) argues that soil nutrient availability not only affects the amount of damage that plants receive from herbivores but the ability of plants to recover from herbivory; however, these two factors are rarely considered together. Describing the effects of soil fertility on both the degree of defoliation and compensation for herbivory for *Brassica nigra* plants damaged by *Pieris rapae* caterpillars, Meyer (2000) found that the percentage defoliation was more than twice as great at low compared to high fertility, even though plants grown at high soil fertility lost a greater absolute amount of leaf area. At both low and high soil fertility, total seed number and mean mass per seed of damaged plants were equivalent to those of undamaged plants. Thus soil fertility did not influence plant compensation in terms of maternal fitness.

Effects of soil fertility practices on pest resistance can be mediated through changes in nutritional content of crops. At equivalent amounts of applied nitrogen (100 and 200 mg per pot), Barker (1975) found that NO_3-N concentrations in spinach leaves (*Spinacia oleracea* L.) were higher when receiving ammonium nitrate than in plants treated with five organic fertilizers. In a comparative study of midwestern USA conventional and organic farmers, Lockeretz et al. (1981) reported organically grown (OG) corn to have lower levels of all amino acids (except methionine) than conventionally grown (CG) corn. Eggert and Kahrmann (1984) also showed CG dry beans (*Phaseolus vulgaris*) to have more protein than OG beans. Consistently higher N levels in the petiole tissue were also found in the CG beans. Potassium and phosphorus levels, however, were higher in the OG beans petioles than in the CG beans. Schuphan (1974) in a long-term comparative study of organic and synthetic fertilizer effects on the nutritional content of four vegetables reported that the OG vegetables consistently contained lower levels of nitrate and higher levels of potassium, phosphorus, and iron than CG vegetables. The above studies suggest that the lower foliar content of NO_3-N of OG crops may be a key factor in determining lower insect damage on crops fertilized with organic amendments.

3. Nitrogen effects

The indirect effects of fertilization practices acting through changes in the nutrient composition of the crop have been reported to influence plant resistance to many insect pests. Among the nutritional factors that influence the level of arthropod damage in a crop, total nitrogen (N) has been considered critical for both plants and their consumers (Mattson, 1980; Scriber, 1984; Slansky and Rodriguez, 1987).

In most studies evaluating aphid and mite response to N fertilization, increases in N rates dramatically increased aphid and mite numbers. According to van Emden (1966) increases in fecundity and developmental rates of the green peach aphid, *Myzus persicae*, were highly correlated to increased levels of soluble N in leaf tissue. Several other authors have also indicated increased aphid and mite populations from N fertilization (Tables 1 and 2). Herbivorous insect

Table 1
Summary of effects of inorganic fertilizers on mite abundance from selected studies (Luna, 1988)

Nutrients	Mite species	Crop	Numerical response of insect[a]
N	*Panonychus ulmi*	Apple	+
N	*Tetranychus telarius*	Apple	+
N	*T. telarius*	Beans	+
N, P, K	*Two-spotted spider mite*	Beans/peaches	+
N	*T. telarius*	Tomato	−
N, P	*T. telarius*	Apples	+/−
N, K	*Bryobia praetiosa*	Beans	+/−
N, Ca	*Heliothrips haemorrhoidalis*	Beans	+/−

[a] Symbols: (+) increase in density with increasing rates of fertilizer element; (−) decrease in density with increasing rates of fertilizer element. Slash separates the effects of fertilizer elements listed in nutrients column.

Table 2
Summary of effects of inorganic fertilizers on aphid abundance from selected studies (Luna, 1988)

Nutrients	Insect species	Crop	Numerical response of insect[a]
N, P, K	*M. persicae*	Tobacco	+/∧/+
N	*Schizaphis graminum* (greenbug)	Oats/rye	−
N, lime	*S. graminum*	Oats	−
N	*R. maidis*	Sorghum	+
N, K, Ca	*M. persicae*	Brussels sprouts	+/∨/−
N, P	*Therioaphis maculate* (spotted alfalfa aphid)	Alfalfa	−/+

[a] Symbols: (+) increase in density with increasing rates of fertilizer element, (∧) highest density occurred at intermediate rates of fertilizer element; (−) decrease in density with increasing rates of fertilizer element; (∨) lowest density occurred at intermediate rates of fertilizer element. Slash separates the effects of fertilizer elements listed in nutrients column.

populations associated with *Brassica* crop plants have also been reported to increase in response to increased soil N levels (Table 3). In a 2-year study, Brodbeck et al. (2001) found that populations of the thrips *Frankliniella occidentalis* were significantly higher on tomatoes that received higher rates of N fertilization. Seasonal trends in *F. occidentalis* on tomato were found to be correlated to the number of flowers per host plant, that changed with the N status of flowers. Plants subjected to higher fertilization rates produced flowers that had higher N content as well as variations in several amino acid profiles that coincided with peak thrips population density. Abundance of *F. occidentalis* (particularly adult females) was most highly correlated to flower concentrations of phenylalanine during population peaks. Other insect populations found to increase following chemical N fertilization included fall armyworm in maize, corn earworm on cotton, pear psylla on pear (*Pyrus* sp.), Comstock mealybug (*Pseudococcus comstocki*) on apple (*Malus* sp.), and European corn borer (*Ostrinia nubilalis*) on field corn (Luna, 1988). Again evidence suggests that high levels of chemical fertilizer applications can cause nutritional imbalances in crops, in turn making them more susceptible to insect disease pressure.

Because plants are a source of nutrients to herbivorous insects, an increase in the nutrient content of the plant maybe argued to increase its acceptability as a food source to pest populations. Variations in herbivore response may be explained by differences in the feeding behavior of the herbivores themselves (Pimentel and Warneke, 1989). For example, with increasing N concentrations in creosotebush (*Larrea tridentate*) plants, populations of sucking insects were found to increase, but the number of chewing insects declined. With higher N fertilization, the amount of nutrients in the plant increases, as well as the amount of secondary compounds that may selectively affect herbivore feeding patterns. Protein digestion inhibitors that accumulated in plant cell vacuoles were not consumed by sucking herbivores, but inhibited chewing herbivores (Mattson, 1980).

In reviewing 50 years of research relating to crop nutrition and insect attack, Scriber (1984) found 135 studies showing increased damage and/or growth of leaf-chewing insects or mites in N-fertilized crops, versus fewer than 50 studies in which herbivore damage was reduced by normal fertilization regimens. In aggregate, these results suggest a hypothesis with implications for fertilizer use patterns in agriculture, namely that high N inputs can precipitate high lev-

Table 3
Response of herbivores to increased soil nitrogen levels on *Brassica* host plants (Letourneau, 1988)

Host plant	Herbivore species	Factor	Response
Brussels sprouts	*M. persicae*	No. of progeny	Increase
Brussels sprouts	*B. brassicae*	No. of progeny	Small increase, dependent on factors such as K
Rape	*Artogeia rapae*	Oviposition frequency	Increase
Kale and cabbage	*A. rapae*	Oviposition frequency	Increase
Kale	*A. rapae*	Oviposition frequency	Increase
Cabbage	*A. rapae*	Growth rate	Increase
Cabbage	*A. rapae*	Growth rate ultimate size	Increase
Cabbage	*Plutella xylostella*	Feeding preference	Increase

els of herbivore damage in crops. As a corollary, crop plants would be expected to be less prone to insect pests and diseases if organic soil amendments were used, these generally resulting in lower N concentrations in the plant tissue. Perhaps achieving more uniform foliar N concentration throughout the year, avoiding pulse high foliar N levels following N fertilizer application, may be a key strategy to achieve optimum crop nutritional levels that deter pest attack.

Letourneau (1988) however questions if the "N-damage" hypothesis, based on Scriber's review, can be extrapolated to a general warning about fertilizer inputs associated to insect pest attack in agroecosystems. Of 100 studies of insects and mites on plants treated experimentally with high and low N fertilizer levels, Letourneau found two-thirds of the studies to show an increase in insect growth, survival, reproductive rate, population densities or plant damage levels in response to increased N fertilizer. The remaining third of the arthropod studies showed either a decrease in damage with fertilizer N or no significant change. The author noted, however, that experimental design can affect the types of responses observed, which poses a problem for insect responses to chemical and organic fertilization treatments.

Firstly, the majority of the studies were conducted with potted plants versus less than 10% conducted in large-scale crop fields, which would have provided a more realistic set of conditions for both plant N uptake and subsequent herbivore response. Secondly, the studies conducted in fields did not clearly support the N-damage hypothesis. Although the sample size was very small, the majority of comparisons showed no significant increase in arthropod performance or damage with increased N. Even in field plot experiments, the results were less than 60% in support of the N-damage hypothesis. Only in greenhouse studies did the N-damage hypothesis hold true. Thirdly, actual damage was measured in only 20% of the studies. Population levels (which could include different insect age classes) may be the next most important predictor of damage, but studies measuring these parameters were not found to support the N-damage hypothesis as much as those measuring parameters of growth, survival, or reproductive rate in individual insect species.

4. The dynamics of insect herbivores in organically managed systems

Studies documenting lower abundance of several insect herbivores in low-input systems have partly attributed such reductions to the lower N content in organically farmed crops (Lampkin, 1990). In Japan, density of immigrants' of the planthopper species *Sogatella furcifera* was significantly lower and the settling rate of female adults and survival rate of immature stages of ensuing generations were generally lower in organic compared to conventional rice fields. Consequently, the density of planthopper nymphs and adults in the ensuing generations was found to decrease in organically farmed fields (Kajimura, 1995).

In England, conventional winter wheat fields exhibited a larger infestation of the aphid *Metopolophium dirhodum* than their organic counterpart (Kowalski and Visser, 1979). The conventionally fertilized wheat crop had higher levels of free protein amino acids in its leaves during June, which were attributed to a N top dressing applied early in April. However, the difference in the aphid infestations between crops was attributed to the aphid's response to the relative proportions of certain non-protein to protein amino acids present in the leaves at the time of aphid settling on crops. The authors concluded that chemically fertilized winter wheat was more palatable than its organically grown counterpart; hence the higher level of infestation.

In greenhouse experiments, when given a choice of maize grown on organic versus chemically fertilized soils collected from nearby farms, European corn borer (*Ostrinia nubilalis*) females significantly laid more eggs in the chemically fertilized plants (Phelan et al., 1995). Interestingly, there was significant variation in egg-laying among chemical fertilizer treatments within the conventionally managed soil, but in plants under the organic soil management, egg-laying was uniformly low. Pooling results across all three farms showed that variance in egg-laying was approximately 18 times higher among plants in conventionally managed soil than among plants grown under an organic regimen. The authors suggested that this difference is evidence for a form of biological buffering characteristically found more commonly in organically managed soils.

Altieri et al. (1998) conducted a series of experiments during 1989–1996 in which broccoli (*Brassica oleraceae*) was subjected to varying fertilization regimes (conventional versus organic). The goal was to test the effects of different N sources on the abundance of the key insect pests, cabbage aphid (*Brevicoryne brassicae*) and flea beetle (*Phyllotreta cruciferae*). Conventionally fertilized monoculture consistently developed a larger infestation of flea beetles and in some cases of the cabbage aphid, than the organically fertilized broccoli systems. The reduction in aphid and flea beetle infestations in the organically fertilized plots was attributed to lower levels of free N in the foliage of plants. This further supports the view that insect pest preference can be moderated by alterations to the type and amount of fertilizer used.

By contrast, a study comparing the population responses of *Brassica* pests to organic versus synthetic fertilizers, measured higher *Phyllotreta* flea beetles populations on sludge-amended collard (*B. oleracea*) plots early in the season compared to mineral-fertilizer-amended and unfertilized plots (Culliney and Pimentel, 1986). However, later in the season, in these same plots, insect population levels were lowest in organic plots for beetles, aphids and lepidopteran pests. This suggests that the effects of fertilizer type varies with plant growth stage and that organic fertilizers do not necessarily diminish pest populations but, at times, may unfortunately increase them. For example, in a survey of California tomato producers, despite the pronounced differences in plant quality (N content of leaflets and shoots) both within and among tomato fields, Letourneau et al. (1996) found no indication that greater concentrations of tissue N in tomato plants were associated with higher levels of insect damage.

5. Changes in pest status due to increased fertilizer use

The majority of Cakchiquel farmers responding to a survey conducted in Patzun, Guatemala, did not recognize herbivorous insects as a problem in their corn *milpas* intercropped with beans, fava (*Vicia fava*), and/or squash (*Cucurbita maxima*, *C. pepo*) (Morales et al., 2001). The farmers attributed this lack of pests to preventative measures incorporated into their agricultural practices, including soil management techniques. Patzun farmers traditionally mixed ashes, kitchen scraps, crop residues, weeds, leaf litter, and manure to produce compost. However, since 1960, synthetic fertilizers were introduced to the region and were rapidly adopted in the area. Today, the majority of farmers have replaced organic fertilizers with urea ($CO(NH_2)_2$), although some recognize the negative consequences of the change and complain that pest populations have increased in their *milpas* since the introduction of the synthetic fertilizers.

In their survey in the Guatemalan highlands, Morales et al. (2001) found that corn fields treated with organic fertilizer (applied for 2 years) hosted fewer aphids (*Rhopalosiphum maidis*) than corn treated with synthetic fertilizer. This difference was attributed to a higher concentration of foliar N in corn in the synthetic fertilizer plots, although numbers of fall armyworm (*Spodoptera frugiperda*) showed a weak negative correlation with increased N levels.

While fertilizers are under utilized in most parts of Asia, over-fertilization does occur in some regions, especially where intensive vegetable production occurs. In addition to the cost, there are ecological and health consequences of excessive fertilization (Conway et al., 1991). Unused N from fertilizer can end up as nitrate in ground water, or in streams especially where intensive vegetable crops are grown in highland areas (i.e. the Philippines, Thailand). A survey of 3000 dug wells in Indian villages showed that about 20% of them contained nitrate levels in excess of the World Health Organization limit of 10 mg of NO_3-N per litter. Increased N levels have also been linked to increased pest problems in rice, notably the plant brownhopper (Santikarm and Perkasem, 2000).

6. Conclusions

Soil fertility management can have several effects on plant quality, which in turn, can affect insect abundance and subsequent levels of herbivore damage. The reallocation of mineral amendments in crop plants can influence oviposition, growth rates, survival and reproduction in the insects that use these hosts (Jones, 1976). Although more research is needed, preliminary evidence suggests that fertilization practices can influence the relative resistance of agricultural crops to insect pests. Increased soluble N levels in plant tissue following N fertilization, was found to generally decrease pest resistance, although this is not a universal phenomenon (Phelan et al., 1995).

Chemical fertilizers can dramatically influence the balance of nutritional elements in plants, and it is likely that their excessive use will create nutrient imbalances, which in turn, reduce resistance to insect pests. Apparently N pulses following high fertilizer applications leads to concentrations of foliar N which make plants more vulnerable to pest attack. In contrast, organic farming practices, apparently promote an increase of soil organic matter and microbial activity and a gradual release of plant nutrients which does not lead to enhanced N levels in plant tissues, thus in theory, allowing plants to derive a more balanced nutrition. Thus, while the amount of N immediately available to the crop may be lower when organic fertilizers are applied, the overall nutritional status of the crop appears to be improved. Organic soil fertility practices can also provide supplies of secondary and trace elements, occasionally lacking in conventional farming systems that rely primarily on artificial sources of N, P, and K. Besides nutrient concentrations, optimum fertilization, which provides a proper balance of elements, can stimulate resistance to insect attack (Luna, 1988). Organic N sources may allow greater tolerance to vegetative damage in plants because such sources release N more slowly, during the course of one to several years.

Phelan et al. (1995) stressed the need to consider mechanisms other than N alone, when examining the link between fertility management and crop susceptibility to insects. Their study demonstrated that the ovipositional preference of a foliar pest can be mediated by differences in soil fertility management. Thus, the lower pest levels widely reported in organic-farming systems may, in part, arise from plant–insect resistances mediated by biochemical

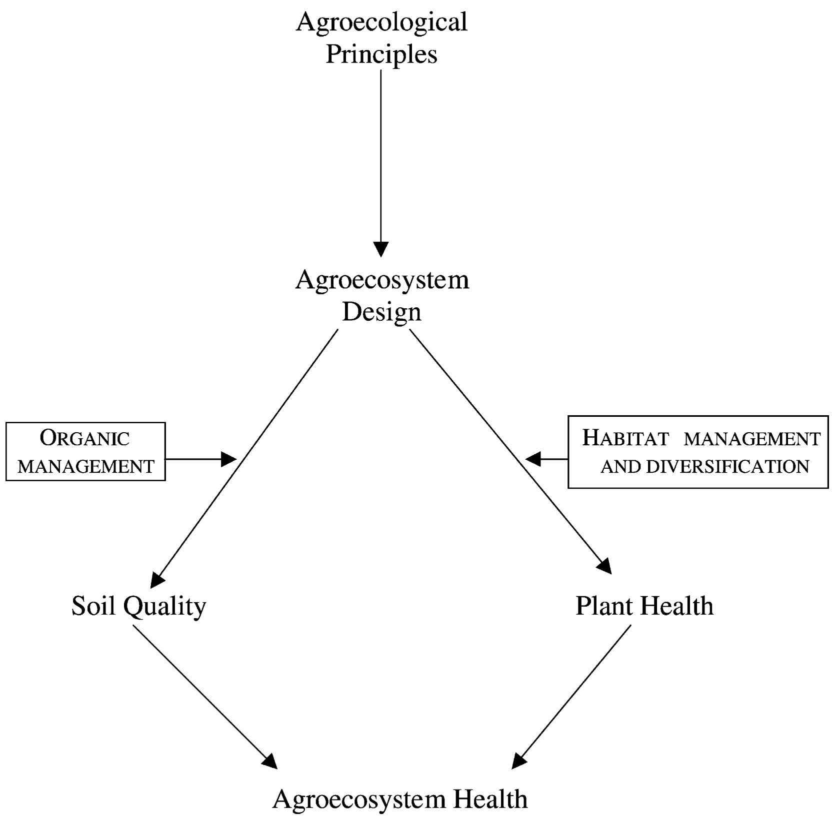

Fig. 2. An approach to agroecosystem health.

or mineral-nutrient differences in crops under such management practices. In fact, we feel such results provide interesting evidence to support the view that the long-term management of soil organic matter can lead to better plant resistance against insect pests.

Clearly more studies comparing pest populations on plants treated with synthetic versus organic fertilizers are needed. Understanding the underlying effects of organic fertilization on plant health may lead us to new and better IPM and ISFM program designs. As we accumulate knowledge regarding the relationships between soil fertility and insect pest attack, we will be better placed to convert conventional systems of crop production to those that incorporate agroecological strategies to optimize soil organic fertilization, crop diversity management and more natural systems of pest regulation without incurring yield penalties (Fig. 2).

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