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Soil, Weed and Insect Management Strategies for Sustainable Agriculture

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Abstract: Soil resources, weed infestations and insect pressures often determine the agronomic and economic sustain ability of tillage and crop management practices throughout the world. This mini-review presents weed, tillage, and entomology results from field studies in the northern U.S. Corn and Soybean Belt to illustrate linkages between soil quality, pest management, and sustainable agriculture. The potential use of decision support tools to examine tradeoffs within complex agricultural systems is also discussed. We conclude that use of no-tillage or reduced tillage and crop rotation are important strategies for sustaining or improving soil quality, primarily because of their impact on soil organic matter. Managing weeds with cover crops or smother plants and disrupting insect pressures by intercropping appear to be practices that can help create more sustainable agroecosystems.

Key words: Soil quality, soil health, weed ecology, cover crops, intercropping, integrated pest management, sustain ability index

Defining and measuring soil quality: The concept of soil quality assessment has been suggested as a tool for evaluating the sustain ability of land-management decisions (Karlen *et al.*, 2001). Defined as "how the soil is functioning" within a field, across farms, or within entire watersheds (Karlen *et al.*, 1997), soil quality cannot be measured directly, but must be inferred by measuring changes in critical soil or ecosystem attributes (Seybold *et al.*, 1997). The assessment process must include both inherent and dynamic indicators (Karlen *et al.*, 2001), with inherent soil quality being determined by the five basic soil forming factors [parent material, climate, time, topography and vegetation (Jenny, 1941) and dynamic soil quality describing the condition soil resources as a result of current and past land use decisions. For the most useful and meaningful soil quality assessments, indicators should (a) relate to ecosystem processes and process-oriented modeling, (b) integrate soil physical, chemical and biological properties and processes, © be accessible to many users and applicable to field conditions, (d) be sensitive to variations in management and climate and where possible, (e) be components of existing soil data bases (Doran and Parkin, 1994). The indicators should also be easily measured and reproducible (Gregorich *et al.*, 1994), as well as sensitive enough to detect changes in the soil resource as a result of human use or degradation (Arshad and Coen, 1992).

One indicator included in almost every soil quality assessment around the world (Seybold *et al.*, 1997; Elmholt *et al.*, 2000; Shepherd, 2000) is soil organic matter (SOM) or one of the more specific SOM fractions such as microbial biomass, water-soluble organic matter, particulate organic matter, or humus/stabilized organic matter. SOM is an important soil quality indicator because it influences numerous soil properties and processes including water retention, aggregate formation, bulk density, pH, buffering capacity, cation exchange, nutrient cycling, agricultural chemical sorption, temperature, spectral environment for plant seedlings, infiltration, aeration, and activity of soil organisms (Kasperbauer and Hunt, 1987; Schnitzer, 1991; Hudson, 1994; Gregorich and Janzen, 1996; Carter, 2002). Adopting soil and crop management practices that maintain or increase SOM is therefore a critical step toward achieving sustain ability.

Tillage and crop rotation effects: Tillage and crop rotation are two management practices that can significantly affect SOM and dynamic soil quality. Karlen *et al.* (1994) found that 10-years of no-tillage on a silt loam soil improved several biological, chemical and physical indicators of soil quality. The improvements enabled the soil to resist degradation through water and wind erosion, accept and retain more water and support higher corn (*Zea mays* L.) yields than with either moldboard plowing or chisel-disking. Leaving crop residues on the soil surface by using conservation or reduced tillage generally reduces soil loss by erosion, increases water use efficiency, and increases surface SOM concentrations (Karlen and Cambardella, 1996). Reducing tillage also decreases the amount of oxygen introduced into a soil, thus preventing aerobic microorganisms from consuming the SOM as a food source (Doran and Smith, 1987).

Kern and Johnson (1993) used geographic databases and published relationships to show that increasing conservation tillage area by 76% could change the soil from an atmospheric C source to a C sink. For many soils, however, the balance between being a C source or sink is fragile. Karlen *et al.* (1998) demonstrated this by quantifying the impact of tillage on SOM loss from land being taken out of the U.S. Conservation Reserve Program (CRP). They showed that if CRP land was plowed, SOM and total N decreased rapidly while bulk density and nitrate-N increased.

Diversifying crop rotations can improve soil quality and increase SOM by mimicking natural ecosystems more closely than current agroecosystems (Karlen and Cambardella, 1996). The effectiveness of different crops is related to the amount of water extracted, photosynthate deposited and persistence of carbon at various soil depths (Kay, 1990). Studies with bromegrass (*Bromus inermis* Leyss.) showed twice the amount of deposition and a much greater resistance to decomposition when compared with corn (Davenport and Thomas, 1988). Many other examples of how reduced tillage and crop rotation affect SOM and soil quality can be found, but that is beyond the scope of this mini-review. Collectively, however, they consistently emphasize that crop diversity and reduced tillage are very important for achieving agricultural sustain ability.

Weed management strategies: Weeds are probably the most ubiquitous class of crop pests. While they seldom cause massive crop failures over vast areas, they are an ever-present nuisance that reduces crop quantity and quality while increasing production costs and human drudgery. If left uncontrolled, the weed populations in many fields are capable of reducing crop yields by more than 80%. Despite routine and intensive attempts to eliminate weeds in world agriculture, direct losses in production quantity and quality continue to occur. As a result, monetary expenditures on herbicides in the developed world far outweigh the expenditures on insecticides or fungicides (Jetsum, 1988). Analysis of the pre-harvest losses caused by weeds in major grain crops suggests that they are similar in amount to those of fungal pathogens and usually exceed losses due to insect pests (Cramer, 1967). In 1965, it was estimated that as a global average, yield loss directly attributable to weeds was about 10%. By 1980, analysis of wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) suggested that despite technological developments in weed control, losses due to weeds remained the same (Ahrens *et al.*, 1981).

Cropping history determines disturbance, inputs and removal patterns within a field, thus regulating the weed community (Buhler, 1995) and dynamic soil quality (Karlen *et al.*, 1998). Continuous cereal cropping creates a predictable habitat for an annual weed with a seasonal recurrence of the same crop type and associated management operations. Conversely, a repeating four-year rotation may be an ephemeral habitat to an annual weed species, whereas to a long-lived perennial there may be underlying predictability. Whether a specific habitat is good or bad for a given species or class of weeds is determined by the generation time and life history of a particular weed species (Cousens and Mortimer, 1995).

The challenge in designing cropping systems that sustain or improve soil quality while minimizing proliferation of well-adapted weed species is creating diversity in space and time. Tactics that are available include (a) using different types and times of soil disturbance through tillage and cultivation, (b) diversifying crop vegetation by using cover crops, rotations, green manures and intercropping and © improving crop competitive ability by planting more competitive crop cultivars and manipulating crop density or spatial pattern. Buhler *et al.* (2001) found that prior to moldboard plowing for the first time in more than 20 years, weed seeds were concentrated in the upper 10 cm of soil. After plowing, weed seeds were distributed more uniformly throughout the upper 20 cm of soil. This distribution remained relatively constant as seed density decline during three years when corn and soybean were being grown. When the field was rotated to oat (*Avena sativa*) and re-seeded with forage species, weed seed numbers increased and they were once again concentrated in the upper 10 cm of the soil profile. Based on these observations, Buhler *et al.* (2001) concluded that the processes affecting weed seed banks in production fields are complex and will vary greatly based on the specific practices used and the timing of their application.

Other management strategies that can influence weed populations and other dynamic soil quality indicators include creating a balanced soil fertility regime, increasing water retention within the root zone, or improving water use efficiency through better rainfall capture, or irrigation methods. Biologically, it may also be possible to differentiate between insects that are specific herbivores for weed species but leave desired species alone versus more generalists that attack crop and weed species indiscriminately. Indigenous or applied pathogens of weeds that do not reduce the competitiveness of the desired crop (Liebman and Janke, 1990) might also be encouraged. Certainly these practices do not eliminate or exclude the use of herbicides. But rather than focusing solely on weed control, the practices should be viewed as options within the entire spectrum of broad scale weed management (Buhler, 1996).

The use of cover or smother crops is one production practice that can reduce soil erosion, improve soil quality and contribute to weed control. Using living plants or plant residues to suppress weeds has been a component of crop production for centuries. Conceptually, the primary goal of using cover crops for weed control is to replace unmanageable weed populations with a manageable cover crop. This is accomplished in modern crop production systems by adjusting the phenology of the cover crop to preempt niches occupied by weeds. Two major types of cover crops exist: off-season cover crops and smother plants. The primary function of off-season cover crops is to produce enough plant residue to alter the soil environment and create a condition that is unfavorable for weed germination and establishment. Smother plants function by displacing weeds through competition and/or suppressing them by allelopathy during the growing season of the harvested crop. Cover and smother crops can also act as "trap crops" for insects or hosts for predators which subsequently protect the primary crops.

Off-season cover crops are planted in the late summer, fall, or early spring and produce most of their biomass before planting a summer crop. Typically, the cover crop is killed or senesces close to planting time, leaving residues on the soil surface or shallowly incorporated into the soil. There are many reports in the literature describing use of cover crops to suppress weeds (Teasdale, 1998). However, there are few reports demonstrating full season weed control without the use of herbicides or tillage. The greatest potential for the use of cover crops in weed control appears to be as a component of an integrated system where the cover crop is used to reduce weed pressures to improve the effectiveness of other control practices.

Smother plants are specialized cover crops, usually grown simultaneously with the harvested crop, developed for their ability to suppress weeds (Dehaan *et al.*, 1994; Buhler *et al.*, 1998). Feasibility of short-term, spring-seeded smother plant systems is supported by plant competition research. For example, weed interference for the first 2 to 8 weeks after corn emergence may not reduce grain yield (Hall *et al.*, 1992; Zimdahl, 1988). Therefore, it is possible that a spring-seeded smother plant could compete with corn for a similar period without reducing crop yields. Other studies show that weeds that do not emerge until 3 to 6 weeks after crops do not reduce yields (Hall *et al.*, 1992). This suggests that if annual weeds can be suppressed for 4 to 6 weeks by the smother plant, crop yields may not be reduced by weeds.

Dehaan *et al.* (1994) concluded that research is needed in three general areas to facilitate development of successful spring-seeded smother plants for a broader range of cropping systems. Studies are needed to: (a) determine effects of various smother plant growth rates and morphologies on crop development and weed control over a wide geographic area to better define the ideotype best suited for use as a smother crop, (b) identify appropriate plant species or to develop them based on the ideotype and © investigate the environmental and economic impacts of adoption of smother plant technology. In addition to these plant-related assessments, the long-term impact on dynamic soil quality indicators and the niches created for weed and other pest complexes need to be quantified as part of evaluation regarding sustain ability of these practices. With regard to soil quality effects, the contribution of these cover and/or smother crops to changes in SOM and the properties/processes that it influences remains to be quantified.

A better understanding of the factors that affect soil quality, ecosystem health, population dynamics of the weeds, and weed and soil response to management practices is needed (Liebman and Gallandt, 1997). We need to integrate weed management and soil quality concepts to include comprehensive theories that include all management variables, building on the foundations provided by the theories and practices of plant and soil ecology, population management, plant protection and cropping systems.

Insect management strategies: Diversifying insect management through more effective biological control and increased vegetational diversity (Risch *et al.*, 1983; Andow, 1991; Theunissen, 1994) is a strategy that can alter herbivore movement patterns and perhaps improve soil quality. Agronomically, such diversification could be achieved by intercropping of two or more crops, planting cover crops, or maintaining selective weedy culture (Altieri *et al.*, 1978; Andow, 1991; Bugg and Wadington, 1994). Grain crop-legume intercropping systems have shown particular promise for insect pest management in tropical agricultural systems. Beans (*Phaseolus* spp.) intercropped with corn have been effective in reducing depredations of leaf hoppers (*Empoasca kraemeri* Ross and Moore), striped cucumber beetle (*Diabrotica balteata* LeConte) and cutworm (*Spodoptera frugiperda* [Smith]) on corn (Altieri *et al.*, 1978). Increased larval parasitism of sorghum shoot fly (*Atherigona soccata* Rondani) was noted if sorghum [*Sorghum bicolor* L. (Moench.)] was intercropped with cowpea [*Vigna unguiculata* (Walp.)] (Zongo *et al.*, 1993). Reduced injury by several pod-boring insects on beans intercropped with corn and higher yields for both crops were also reported (Karel, 1993).

In temperate regions, there are fewer examples of successful pest management through intercropping, although reductions of insect pest populations have been attained by mixing high-value vegetable crops (Theunissen, 1994). Strip intercropping of corn, soybean [*Glycine max* (L) Merr.] and oats (*Avena sativa* L.) has been examined as an alternative cropping system (Ghaffarzadeh *et al.*, 1994) because of its potential for increasing grain yield from the outer rows of corn and the greater temporal and spatial diversity it creates across a field. This increased crop diversity may help reduce pest populations, particularly where crops are rotated (Francis and Clegg, 1990) for control of host-specific pests such as corn rootworms, *Diabrotica* spp. (Coleoptera: Chrysomelidae). This type of plant manipulation can affect dynamic soil quality because it creates niches for various insects and other organisms within the soil. These niches presumably reflect variations in residue quality and quantity, rates of decomposition and various microbially-mediated processes (eg., respiration, energy production and nutrient cycling).

An example of how soil, crop and insect management practices interact and thus affect soil quality and long-term sustain ability can be illustrated by examining strip intercropping effects on corn rootworms. The latter are key pests affecting corn grown in temperate zones of North America. These insects generally are host-specific to corn, so annual crop rotation between corn and soybean has become the predominant pest management strategy used by corn producers. However, this strategy has been increasingly ineffective for managing northern corn rootworms (*Diabrotica barberi,* Smith and Lawrence), because this species has adapted to crop rotation by selection for extended egg diapause (Krysan *et al.*, 1984; Ostlie, 1987). This adaption allows eggs to survive in the soil through two growing seasons until corn is planted again in the rotation. Also, some populations of western corn rootworms (*Diabrotica virgifera virgifera*, LeConte) are no longer managed effectively by annual corn–soybean rotation, because they apparently have adapted behaviorally by ovipositing in soybean fields during the non-corn phase of the rotation (Edwards *et al.*, 1996). Longer rotations that extend the reoccurrence of corn beyond two years may be necessary to manage these behaviorally-adapted populations of corn rootworms (Krysan *et al.*, 1984).

Ghaffarzadeh *et al.* (1994) and Garcia-Préchac (1991) hypothesized that a 3 year strip intercropping rotation could provide the ecosystem diversity needed to manage behaviorally-adapted or extended-diapause rootworm populations. Field studies conducted to evaluate their hypothesis showed that the outside rows of corn sustained infestations of western corn rootworm (Boeve, 1992; Ellsbury *et al.*, 999), apparently because the larvae were able to migrate into the current corn crop from adjacent strips where corn was grown in previous years (Table 1).

Table 1: Row-specific root injury scores for corn naturally infested with corn rootworm near Spencer, Iowa, USA.

	Root injury rating[†]		
Row[‡]	1995	1996	1997
1	6.9 ± 0.2a	2.9 ± 0.2a	4.6 ± 0.5a
2	2.0 ± 0.5b	1.1 ± 0.1b	1.3 ± 0.2b
3	1.8 ± 0.3b	1.2 ± 0.1b	1.0 ± 0.0b
4	1.8 ± 0.2b	1.0 ± 0.0b	1.2 ± 0.1b
5	1.8 ± 0.2b	1.0 ± 0.0b	1.1 ± 0.1b
6	2.4 ± 0.6b	1.2 ± 0.1b	1.7 ± 0.3b

[†] Values are means ±SEM, means within a column followed by the same letter were not significantly different using Fisher's protected LSD, $P < 0.05$.

[‡] Row numbers correspond to the distance (~75 cm each) from the same crop planted the previous year (i.e. row 1 is outside, closest to corn residue).

Table 2: Cultural and insecticidal soil treatment effects on the number of emerged western corn rootworm adults and root-injury ratings for corn plants grown within the outside row of a strip-intercropped system that was naturally infested in 1996 and 1997 and artificially infested in 1997

Treatment[†]	Adults / 0.5m^2	Root injur
	1996	
NI-control	10.5±5.6a	2.9±0.2b
NI-insecticide	2.0±0.8b	1.9±0.4c
NI-ripped	9.0±4.8a	4.1±0.4a
NI-oilseed meal	3.0±0.8b	2.8±0.3b
	1997	
NI-control	27.2±2.4b	3.2±0.8b
I-control	53.3±4.6a	6.8±0.7a
I-insecticide	1.6±0.8c	1.5±0.3b
NI-ripped	10.0±1.4c	2.9±0.3b
I-ripped	48.0±4.9a	6.5±0.9a
NI-compacted	3.6±0.9c	2.4±0.9b
I-compacted	28.4±5.2b	3.5±1.1b

[†] NI = naturally infested; I = artificially infested;

[‡] Means within a column for each year followed by the same letter were not significantly different using Fisher's protected LSD, $P < 0.05$

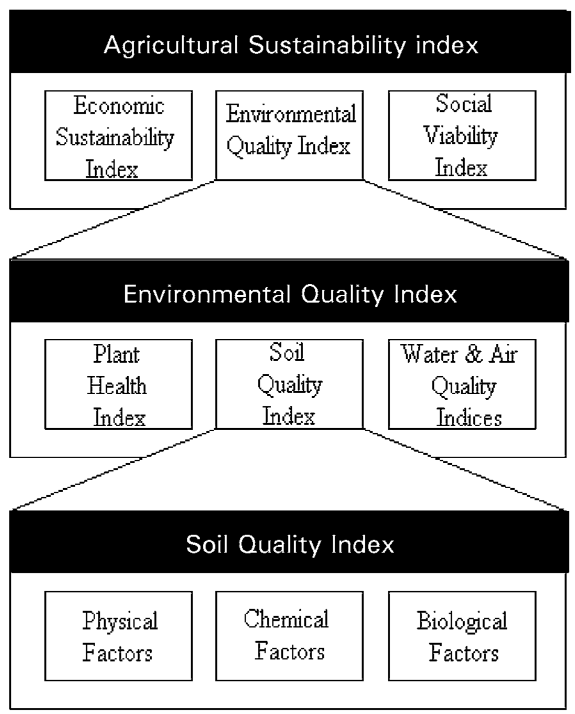

Fig. 1: Hierarchy of agricultural indices showing the conceptual relationship between soil quality evaluations and sustainable land management (Adapted from Andrews, 1998)

Emergence of adult corn rootworm and root injury (Ellsbury *et al.*, 1999) were both reduced by applying a cruciferous oilseed meal treatment between current corn strips and those infested with rootworm eggs during the previous year. The oilseed meal treatment was nearly as effective as insecticide treatment (Table 2) in reducing root injury and numbers of emerging adult corn rootworms in corn rows adjacent to egg-infested soybean strips. The promising results from this treatment suggest that in agricultural areas where cruciferous oilseed meal is available as a by-product of oil extraction, its application as a barrier against corn rootworms may be feasible. As a natural by-product, the use of this material for insect control may be more socially acceptable and therefore sustainable, than pesticide-based strategies. It may also be more economically sustainable because premium prices are often available for products grown using organic production practices instead of synthetic chemical controls.

To create additional plant species diversity, oilseed crops, *Brassica* or *Crambe* spp., could be grown as the third crop in a strip intercropped rotational system. Incorporation of cruciferous plant residue into the soil after harvest may also be able to prevent movement of corn rootworm larvae into the outside corn rows. Such amendments could also have an effect on soil quality, although such measurements were not included in these studies.

Tillage can also affect adult rootworm emergence and root injury scores (Ellsbury *et al.*, 1999; Gustin and Schumacher, 1989). For example, ripping the soil between corn rows with a cultivator shank, increased soil porosity and apparently facilitated larval movement into adjacent corn strips (Table 2). However, when outer rows of corn planted adjacent to soybean strips that were subjected to interrow soil compaction, fewer adult rootworms emerged and less root injury was observed.

Based on these studies, the risk of significant root injury and subsequent yield loss within the outside corn rows will increase with long-term strip intercropping on the same ground (Boeve, 1992). Where alternatives to soil insecticide use are sought, deliberate wheel traffic compaction of the interrow soil may reduce infestation potential. This approach has several disadvantages including additional traffic through the field, higher fuel costs, and fabrication or construction of a compaction wheel. It may also negatively affect soil quality especially if the compaction is done when the soil is wet. A periodic shift in strip placement by an additional one-half strip width is another noninsecticidal management strategy for controlling corn rootworms. The extra shift in strip position would result in a greater distance between egg-infested corn ground and the current year's crop that would be too large for effective rootworm larval migration. Unfortunately, this also requires additional time and increases the management complexity for the farmer. Finally, it is important to stress that for which ever management strategy is chosen, the plant and insect evaluations must be complemented by analysis of soil quality indicators if the entire system is to be understood and the most sustainable management practices are to be identified and implemented.

Decision aids for complex system evaluations: As previously stated, The goal for this mini-review is to examine soil, weed, and insect management strategies that could result in more sustainable agricultural practices. But how can producers effectively consider the multitude of factors affected by those management strategies? One approach is to develop decision tools that can help organize and interpret the information that is available for each of the critical endpoints (i.e., soil quality, weed management and insect suppression). Such tools are often helpful for assessing sustain ability of agricultural systems because of the increased management inputs that must be considered (Madden, 1990; Edwards *et al.*, 1993).

One decision support system (DSS) developed to assist farmers, ranchers and other land managers examines farm management effects on water quality and economics (Yakowitz *et al.*, 1993). This hierarchical DSS operates as a spreadsheet macro and allows the decision maker to assign a priority order (ranks) to indicators without having to set specific weights. A similar predictive hierarchical model was used to evaluate environmental and economic outcomes for poultry litter management (Andrews and Carroll, 2001). Indicator weights were required only to compare relative outcomes based on different stakeholders' values. Another hierarchical decision tool using statistics to identify indicators and determine appropriate weighting factors assessed soil quality in vegetable production systems (Andrews *et al.*, 2001). Fig. 1 illustrates the hierarchical structure of DSS tools and the relationship between soil quality and agricultural sustain ability. This approach could be used to examine tradeoffs between weed management, insect suppression and soil quality indicators, but we did not attempt to do so.

The goal for this mini-review is to show the multiple linkages among dynamic soil quality and alternative weed, insect and tillage management strategies that can be used to create more sustainable agricultural production systems. The use of no-till or reduced tillage and crop rotation are recommended because they will generally sustain or improve soil quality by maintaining or increasing SOM levels. Although the specific practices will differ from region to region, those that preserve or increase soil organic matter, take advantage of natural plant competition and disrupt insect, weed and pathogen life cycles are expected to be most effective and sustainable. Weed management strategies incorporating cover crops, smother plants, and soil manipulation may provide solutions to problems associated with current weed management systems. These alternatives could provide management flexibility, not only as new weed control options, but also as strategies to control soil erosion and improve soil quality by increasing soil cover and organic matter input throughout the growing season. Development and refinement of intercropping systems to achieve spatial vegetational diversity also show promise for enhancing the ecological sustain ability of many agroecosystems and helping achieve the sustainable agricultural goals that producers and consumers throughout the world desire.

References

Ahrens, C., H. H. Cramer, M. Mogk and H. Peschel, 1981. Economic impact of crop losses. pp: 65-73. In: Proceedings of the Tenth International Congress of Plant Protection, Croyden, UK.

Altieri, M. A., C. A. Francis, A. Van Schoonhoven and J. D. Doll, 1978. A review of insect prevalence in maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.) polycultural systems. Field Crops Res., 1:33-49.

Andow, D. A., 1991. Vegetational diversity and arthropod population response. Annu. Rev. Entomol., 36:561-596.

Andrews, S. S., 1998. Creating a minimum data set to compare soil quality under poultry litter management alternatives. In: Sustainable Agriculture Alternatives: Ecological and managerial implications of poultry litter management alternatives applied to agronomic soils. Ph.D. Dissertation, University of Georgia, Athens, GA, pp: 68-109.

Andrews, S. S. and C. R. Carroll, 2001. Soil quality assessment: an ecological paradigm using a poultry litter management case study. Ecological Appln, (in press)

Andrews, S. S., D. L. Karlen and J. P. Mitchell, 2001. A comparison of soil quality indexing methods for vegetable production systems in northern California. Agric. Ecosyst. Environ. (in press).

Arshad, M. A. and G. M. Coen, 1992. Characterization of soil Quality: Physical and chemical criteria. Am. J. Altern. Agric., 7:25-31.

Boeve, P. J., 1992. Impact of strip intercropping on the corn rootworm and European corn borer in Iowa. M.Sc. thesis, Iowa State University, Ames.

Bugg, R. L. and C. Wadington, 1994. Using cover crops to manage arthropod pests of orchards: a review. Agric. Ecosyst. Environ., 50:11-28.

Buhler, D. D., 1995. Influence of tillage systems on weed population dynamics and management in corn and soybean production in the central USA. Crop Sci., 35:1247-1257.

Buhler, D. D., 1996. Development of alternative weed management strategies. J. Prod. Agric., 9:501-504.

Buhler, D. D., K. A. Kohler and M. S. Foster, 1998. Spring-seeded smother plants for weed control in corn and soybean. J. Soil Water Conserv, 53:272-275.

Buhler, D. D., K. A. Kohler and R. L. Thompson, 2001. Weed seed bank dynamics during a five-year crop rotation. Weed Technol., 15:170-176.

Carter, M. R., 2002. Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. Agron. J., 94:000-000. (in press) (accepted September, 2001)

Cousens, R. and M. Mortimer, 1995. Chapter 6: Extrinsic factors affecting population density. pp. 169-216. In: Dynamics of Weed Populations, Cambridge University Press, Cambridge, U.K.

Cramer, H. H., 1967. Plant protection and world crop production. Pflanzenschutznachrichten, 20:15-24.

Davenport, J. R. and R. L. Thomas, 1988. Carbon partitioning and rhizodeposition in corn and bromegrass. Can. J. Soil Sci., 68:693-701.

Dehaan, R. L., D. L. Wyse, N. J. Ehlke, B. D. Maxwell and D. H. Putnam, 1994. Simulation of spring-seeded smother plants for weed control in corn (*Zea mays*). Weed Sci., 42:35-43.

Doran, J. W. and M. S. Smith, 1987 Organic matter management and utilization of soil and fertilizer nutrients. pp: 53-72. In R.F. Follett, J. W. B. Stewart and C.V. Cole (eds.) Soil Fertility and Organic Matter as Critical Components of Production Systems, Spec. Publ. 19. ASA-CSSA-SSSA, Madison, WI.

Doran, J. W. and T. B. Parkin, 1994. Defining and assessing soil quality. pp: 3-21. In: J. W. Doran, D. C. Coleman, D. F. Bezdicek and B. A. Stewart (eds.) Defining Soil Quality for a Sustainable Environment. SSSA Spec. Publ. No. 35. Soil Sci. Soc. Am. and Am. Soc Agron., Inc., Madison, WI.

Edwards, C. A., T. L. Grove, R. R. Harwood and C. J. P. Colfer, 1993. The role of agroecology and integrated farming systems in agricultural sustain ability. Agric. Ecosyst. Environ., 46:99-121.

Edwards, C. R., L. W. Bledsoe and J. L. Obermeyer, 1996. The dramatic shift of the western corn rootworm, *Diabrotica virgifera* LeConte (Coleoptera: Chrysomelidae), to maize in rotation with soybeans in Indiana. pp: 469. In: Proceedings, XX International Congress Entomol., Florence, Italy.

Ellsbury, M. M., D. E. Exner and R. M. Cruse, 1999. Movement of corn rootworm larvae between border rows of soybean and corn in a strip intercropping system. J. Econ. Entomol., 92:207-214.

Elmholt, S., B. Stenberg, A. Grønlund and V. Nuutinen, 2000. Soil Stresses, Quality and Care. Proc. NJF Seminar 310, April 10-12, 2000. Ås, Norway, DIAS Report No. 38, Plant Production, Tjele, Denmark, pp: 179.

Francis, C. A. and M. D. Clegg, 1990. Crop rotations in sustainable production systems. pp: 107-122. In: C. A. Edwards, R. Lal, P. Madden, R. H. Miller and G. House (eds.) Sustainable Agricultural Systems. Soil and Water Conserv. Soc., Inc., Ankeny, IA.

Garcia-Préchac, F., 1991. Strip position, tillage, and water regime effects on a strip intercropping rotation. Ph.D. dissertation, Iowa State University, Ames.

Ghaffarzadeh, M., F. Garcia-Préchac and R. M. Cruse, 1994. Grain yield response of corn, soybean, and oat grown in a strip intercropping system. Am. J. Altern. Agric., 9:171-177.

Gregorich, E. G., M. R. Carter, D. A. Angers, C. M. Monreal and B. H. Ellert, 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci., 74:367-385.

Gregorich, E. G. and H. H. Janzen, 1996. Storage of soil carbon in the light fraction and macroorganic matter. pp: 167-190. In M. R. Carter and B.A. Stewart (ed.) Structure and Organic Matter Storage in Agricultural Soils. Lewis Pub., CRC Press, Boca Raton, FL.

Gustin, R. D. and T. E. Schumacher, 1989. Relationship of some soil pore parameters to movement of first-instar western corn rootworm (Coleoptera: Chrysomelid). Environ. Entomol., 18:343-346.

Hall, M. R., C. J. Swanton and G. W. Anderson, 1992. The critical period of weed control in grain corn (*Zea mays*). Weed Sci., 40:441-447.

Hudson, B. D., 1994. Soil organic matter and available water capacity. J. Soil Water Conserv., 49:189-194.

Jenny, H., 1941. Factors of Soil Formation. McGraw-Hill, NY, pp: 281.

Jetsum, A. R., 1988. Commercial application of biological control: status and prospects. Philosophical Transactions of the Royal Society of London, B 318:357-373.

Karel, A. K., 1993. Effects of intercropping with maize on the incidence and damage caused by pod borers of common beans. Environ. Entomol., 22:1076-1083.

Karlen, D. L., N. C. Wollenhaupt, D. C. Erbach, E. C. Berry, J. B. Swan, N. S. Eash and J. L. Jordahl, 1994. Long-term tillage effects on soil quality. Soil Tillage Res., 32:313-327.

Karlen, D. L. and C. A. Cambardella, 1996. Conservation strategies for improving soil quality and organic matter storage. pp: 395-420. In M. R. Carter and B.A. Stewart (eds.) Structure and Organic Matter Storage in Agricultural Soils. Lewis Pub., CRC Press, Boca Raton, FL.

Karlen, D. L., M. J. Mausbach, J. W. Doran, R. G. Cline, R. F. Harris and G. E. Schuman, 1997. Soil quality: A concept, definition, and framework for evaluation (A guest editorial). Soil Sci. Soc. Am. J., 61:4-10.

Karlen, D. L., J. C. Gardner and M. J. Rosek, 1998. A soil quality framework for evaluating the impact of CRP. J. Prod. Agric., 11:56-60.

Karlen, D. L., S. S. Andrews and J. W. Doran, 2001. Soil quality: current concepts and applications. Adv. Agron., 74:1-40.

Kasperbauer, M. J. and P. G. Hunt, 1987. Soil colour and surface residue effects on seedling light environment. Plant and Soil, 97:295-298.

Kay, B. D., 1990. Rates of change of soil structure under different cropping systems. Adv. Soil Sci., 12:1-52.

Kern, J. S. and M. G. Johnson, 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Am. J., 57:200-210.

Krysan, J. L., J. J. Jackson and A. C. Lew, 1984. Field termination of egg diapause in *Diabrotica* with new evidence of extended diapause in *D. Barberi*. Environ. Entomol., 13:1237-1240.

Liebman, M. and R. R. Janke, 1990. Sustainable weed management practices. pp: 111-143. In: C. A. Francis, C. B. Flora and L. D. King (eds.) Sustainable Agriculture in Temperate Zones. Wiley, New York.

Liebman, M. and E. R. Gallandt, 1997. Many little hammers: ecological management of crop-weed interactions. pp: 291-341. In L. Jackson (ed.) Ecology in Agriculture. Academic Press, New York.

Madden, J. P., 1990. The economics of sustainable low-input farming systems. p. 315-341. In: C. A. Francis, C. B. Flora and L. D. King (eds.) Sustainable agriculture in temperate zones. John Wiley & Sons, Inc., New York.

Ostlie, K. R., 1987. Extended diapause: northern corn rootworm adapts to crop rotation. Crop Soils Mag., 39:23-25.

Risch, J., D. Andow and M. A. Altieri, 1983. Agroecosystem diversity and pest control: Data tentative conclusions and new research directions.. Environ. Entomol., 12:625-629.

Schnitzer, M., 1991. Soil organic matter and soil quality. pp: 33-49. In: S. P. Mathur, and C. Wang (eds.) Soil quality in the Canadian context: 1988 discussion papers. Tech. Bull. 1991-1E. Land Resource Research Centre, Research Branch, Agriculture Canada, Ottawa, Ontario.

Seybold, C. A., M. J. Mausbach, D. L. Karlen and H. H. Rogers, 1997. Quantification of soil quality. pp: 387-404. In: R. Lal, J. M. Kimble, R. F. Follett and B. A. Stewart (eds.) Soil Processes and the Carbon Cycle. CRC Press, Inc., Boca Raton, FL.

Shepherd, T. G., 2000. Visual soil assessment. Vol. 1. Field guide for cropping and pastoral grazing on flat to rolling country. Horizons. MW & Landcare Research, Palmerston North, New Zealand, pp: 84.

Teasdale, J. R., 1998. Cover crops, smother plants and weed management. pp: 247-270. In: J. L. Hatfield, D. D. Buhler and B. A. Stewart (eds.) Integrated Weed and Soil Management. Ann Arbor Press, Chelsea, MI.

Theunissen, J., 1994. Intercropping in field vegetable crops: pest management by agroecosystem diversification – an overview. Pesticide Sci., 42:65-68.

Yakowitz, D. S., J. J. Stone, L. J. Lane, P. Heilman, J. Masterson, J. Abolt and B. Imam, 1993. A decision support system for evaluating the effect of alternative farm management systems on water quality and economics. Wat. Sci. Tech., 28: 47-54.

Zimdahl, R. L., 1988. The concept and application of critical weed-free period. pp: 145-155. In: M. A. Altieri and M. Liebman (eds.) Weed Management in Agroecosystems: Ecological Approaches. CRC Press, Inc., Boca Raton, FL.

Zongo, J. O., C. Vincent and R. K. Stewart, 1993. Effects of intercropping sorghum-cowpea on natural enemies of the sorghum shoot fly, *Atherigona soccata* (Diptera: Muscidae), in Burkina Faso. Biol. Agric. Hort., 9:201-213.