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Systematic method for rating soil quality of conventional, organic, and integrated apple orchards in Washington State

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Abstract

Much remains to be known concerning the complex relationships between specific soil property measurements and overall soil quality. The objective of this study was to advance our understanding of these complex relationships by further developing and applying a systematic method for evaluating the effects of conventional, integrated and organic apple production systems on soil physical, chemical, and biological properties using a modified soil quality index. This index utilizes 1998 soils data from these three treatments. The study used four, 0.14 ha replicates of each of the three treatments in a randomized complete block design. Experimental plots were planted to 'Golden Delicious' apples (*Malus domestica* Borkh.) in 1994 on a commercial orchard in the Yakima Valley of Washington state. Organic soil management practices included additions of composted poultry manure and bark mulches and the use of mechanical tillage for weed control. Conventional soil management practices included additions of synthetic fertilizers and the use of herbicides for weed control. The integrated system utilized practices from each of the other two systems. Increased aggregate stability, microbial biomass, and earthworm abundance were associated with improved soil quality under integrated management when compared to conventional management in 1998. Organic management resulted in lower soil bulk densities and generally improved biological soil properties compared to conventional management. Few significant differences in soil properties were measured between the integrated and organic systems. The integrated production system received a soil quality index rating of 0.92 (out of 1.00), which was significantly higher than the index rating of 0.78 for the conventional production system; the organic production system received a rating of 0.88, which was not significantly different from the other two systems. The study indicates that a well-developed soil quality index can provide an effective framework for evaluating the overall effects of different orchard production practices on soil quality.

Keywords: Compost; Integrated farming; Orchard management; Organic farming; Soil quality index

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1. Introduction

Washington state, the leading apple producer in the US, harvested 2.3 million tonnes of apples from nearly 63,000 ha in 1997 (Washington State Department of Agriculture, 1998). As apple production in Washington state has intensified to meet market demands over the past decades, concerns in the marketplace and on the farm about the negative impacts of conventional food production practices on human health (Hardell and Eriksson, 1999) and environmental quality (Doran et al., 1996; Williamson et al., 1998) have

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also increased. These concerns have led to increased grower interest in developing environmentally sound management practices.

Organic and integrated apple management systems offer alternative practices that address environmental concerns (National Research Council, 1989; Conacher and Conacher, 1998). Organic management practices exclude chemical pesticide and fertilizer inputs and use naturally derived products as defined by organic certification programs. Integrated farming systems, successfully adopted in some of the major apple growing regions in Europe (Sansavini, 1997), utilize methods of conventional and organic production systems in an attempt to optimize both environmental quality and economic profit. Although studies have found that alternative management practices may improve soil quality as compared to conventional management practices (Reganold et al., 1987, 1993; Gunapala and Scow, 1998; Swezey et al., 1998), to our knowledge no study has specifically compared the effects of conventional, organic, and integrated management on soil quality in apple orchards.

Doran and Parkin (1994) defined soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health." Accurate, consistent assessment of soil quality requires a systematic method for measuring and interpreting soil properties that adequately serve as soil quality indicators (Granatstein and Bezdicek, 1992). Although such methods exist for monitoring and evaluating air and water quality, no single method has been widely accepted for assessing soil quality due to the great complexity and variability of soil systems.

Much remains to be known concerning the complex relationships between specific soil property measurements and overall soil quality. Advancement of our understanding of these relationships requires development and application of a methodology for assessing and monitoring soil quality as already exists for air and water quality assessments. The objective of this study was to further develop and apply an existing systematic method for evaluating the effects of conventional, organic, and integrated apple production systems on soil quality. Such an evaluation methodology advances understanding of soil ecosystem relationships and aids in the interpretation of soil data for apple production systems.

2. Soil quality index

2.1. Rating soil quality

Several systematic approaches have been taken to develop an integrated soil quality index. Pierce and Larson (1993) proposed using statistical quality control procedures to assess dynamic temporal changes in soil quality. Smith et al. (1993) employed multiple variable kriging, based on nonparametric geostatistics, to determine soil quality probabilities for a land area in order to integrate soil quality indicators into an index. Doran and Parkin (1994) recommended using a simpler multiplicative function to assess soil quality; such a framework takes into account geographical, climatic, and socioeconomic concerns. Karlen and Stott (1994) utilized normalized scoring curves developed through a systems engineering approach (Wymore, 1993) for evaluating a production system's effect on soil quality. The resulting soil quality index was applied in comparison studies of conservation reserve program sites and grain cropping systems (Karlen et al., 1994a, b; Harris et al., 1996; Hussain et al., 1999). Karlen and Stott (1994) chose important soil functions associated with soil quality, such as accommodating water entry, accommodating water transfer and absorption, resisting surface degradation, and supporting plant growth, to evaluate the effects of the different soil management systems on soil quality.

For this study, the approach suggested by Karlen and Stott (1994) was chosen due to its flexibility, ease of use, and its potential for interactive use by apple producers. Their system uses selected soil functions, which are weighted and integrated according to the following expression:

$$\begin{aligned}\text{Soil quality} &= q_{\mathrm{WE}}(\mathrm{wt}) + q_{\mathrm{WMA}}(\mathrm{wt})\\ &\quad + q_{\mathrm{RD}}(\mathrm{wt}) + q_{\mathrm{FQP}}(\mathrm{wt})\end{aligned} \tag{1}$$

where q_{WE} is the rating for the soil's ability to accommodate water entry, q_{WMA} is the rating for the soil's ability to facilitate water transfer and absorption, q_{RD} is the rating for the soil's ability to resist degradation, q_{FQP} is the rating for the soil's ability to sustain plant growth, wt is the numerical weight for each soil function.

Investigators using this soil quality index can assign numerical weights (wt) to each soil function

Table 1
Soil quality index framework

Function	Weight	Indicator Level 1	Weight	Indicator Level 2	Weight
Accommodate water entry	0.25	Aggregate stability (0–7.5 cm)	0.40		
		Bulk density (0–7.5 cm)	0.40		
		Earthworms (0–7.5 cm)	0.20		
Facilitate water movement and availability	0.25	Water-filled pore space (0–15 cm)	0.40		
		Porosity (0–15 cm)	0.25		
		Organic carbon (0–15 cm)	0.25		
		Earthworms (0–15 cm)	0.10		
Resist surface structure degradation	0.25	Aggregate stability (0–7.5 cm)	0.40		
		Organic carbon (0–7.5 cm)	0.40		
		Microbial processes	0.20	Microbial biomass carbon (0–7.5 cm)	0.40
				Microbial biomass nitrogen (0–7.5 cm)	0.40
				Water-filled pore space (0–15 cm)	0.20
Sustain fruit quality and productivity	0.25	Cation exchange capacity (0–15 cm)	0.20		
		Organic carbon (0–15 cm)	0.20		
		pH (0–15 cm)	0.10		
		Microbial processes	0.10	Microbial biomass carbon (0–15 cm)	0.40
				Microbial biomass nitrogen (0–15 cm)	0.40
				Water-filled pore space (0–15 cm)	0.20
		Total nitrogen (0–15 cm)	0.10		
		Nitrate nitrogen (0–15 cm)	0.10		
		Extractable Phosphorus (0–15 cm)	0.10		
		Electrical conductivity (0–15 cm)	0.10		

according to their interpretation of the soil function's importance in fulfilling the overall goals of maintaining soil quality under specific soil conditions and land-use purposes. Quantifying numerical weights may take into account socioeconomic concerns, specific research aims, cropping requirements, the farmer's needs, and environmental concerns. Weights for all soil functions must sum to 1.0. An ideal soil would fulfill all the functions considered important and, under the proposed framework, be given a score of 1.0. As a soil fails to meet the ideal criteria, its score would fall, with zero being the lowest rating. Associated with each soil function are soil quality indicators that influence, to varying degrees, that particular function. Level 1 indicators are most directly associated with the soil function (Table 1), whereas higher-level indicators are less directly associated with the soil function. As with soil functions, numerical weights assigned to select soil quality indicators must sum to 1.0 at each level.

2.2. Scoring functions

Numerical weights for each soil quality indicator are multiplied by indicator scores calculated through the use of the standardized scoring functions that normalize indicator measurements to a value between 0 and 1.0. Scoring curves are generated from the following equation (Wymore, 1993):

$$\text{Normalized score}(v) = \frac{1}{[1+((B-L)/(x-L))^{2S(B+x-2L)}]} \quad (2)$$

where B is the baseline value of the soil property where the score equals 0.5, L is the lower threshold, S is the slope of the tangent to the curve at the baseline, x is the soil property value.

Using the scoring curve equation, three types of standardized scoring functions typically used for soil quality assessment can be generated: (1) 'More is better,’ (2) ‘Less is better,’ and (3) ‘Optimum.’ The equation defines a ‘More is better’ scoring curve for positive slopes, a ‘Less is better’ curve for negative slopes, and an ‘Optimum’ curve when a positive curve is reflected at the upper threshold value.

‘More is better’ curves score soil properties that are associated with improved soil quality at higher levels (Fig. 1a). Aggregate stability, for example, plays a key role in a soil’s ability to resist structural degradation due to wind and rain (Kemper and Rosenau, 1986). Total nitrogen, cation exchange capacity (CEC), organic carbon, microbial biomass carbon (MBC) and nitrogen (MBN), and earthworm populations would also be scored with a ‘More is better’ curve.

‘Less is better’ curves score soil quality indicators, such as bulk density, that indicate poor soil quality at high levels (Fig. 1b). Higher bulk densities of compacted soils result in decreased root development and infiltration rates leading to poor plant growth and the potential for runoff of surface water (Arshad et al., 1996).

‘Optimum’ curves score those properties that have an increasingly positive influence on soil quality up to an optimal level beyond which their influence is detrimental (Fig. 1c). The presence of nitrate in the rooting zone, for example, is essential for plant growth and fruit development. Its presence at high levels, however, increases the potential for groundwater contamination (Doran et al., 1996) and lower fruit quality and storability (Bramlage et al., 1980). Other soil quality indicators such as porosity, water-filled pore space, extractable phosphorus, pH, and electrical conductivity (EC) would be rated using this type of curve.

The shape of the curves (Fig. 1a–c) generated by the scoring curve equation is determined by critical values. Critical values include threshold and baseline values, which are based on expert opinion, published values, or measured values observed under near-ideal soil conditions for the specific site and crop (Karlen et al., 1994a, b; Harris et al., 1996). Threshold values are soil property values where the scoring function equals one when the measured soil property is at an optimal level or equals zero when the soil property is at an unacceptable level. Baseline values are soil property values where the scoring function equals 0.5 and equal the midpoints between threshold soil property values. Slopes of scoring curves at the baseline point may be determined using the optimization functions in computer spreadsheet software programs.

2.3. Soil quality score card

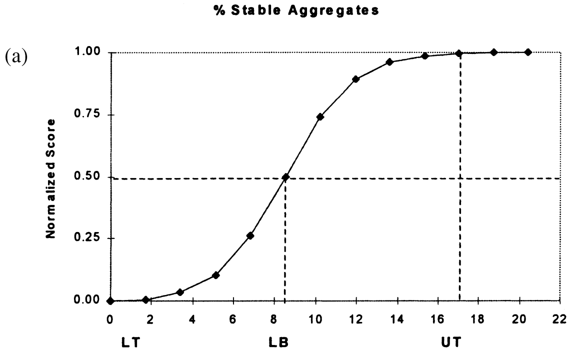
After scoring all soil quality indicators, soil function scores are determined by summing the products of the numerical weights of their associated indicators and the normalized soil parameter scores. Soil function scores are then summed to give an overall soil quality score. The resulting soil quality score card, an example of which appears in Table 2, provides specific information on the soil’s ability to fulfill particular functions. Weights assigned to soil functions may be changed to reflect the priorities and specific needs of researchers and growers thereby making the score card a useful tool for soil quality interpretation from multiple perspectives.

Such a rating system provides not only a simple, integrated rating of soil quality but also, more importantly, a systematic framework outlining the assumptions made in assessing soil quality. Overtly stating the assumptions underlying the evaluation facilitates refinement of the system in other studies and thereby furthers our understanding of the complex issues relating to soil quality. Used for a period of years to evaluate different systems, this assessment index may help determine trends and rates of change associated with a particular management system, allowing for development of best management practices for specific regions and cropping systems.

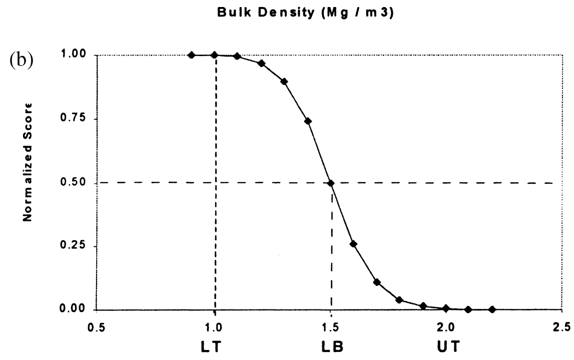
3. Materials and methods

3.1. Study area

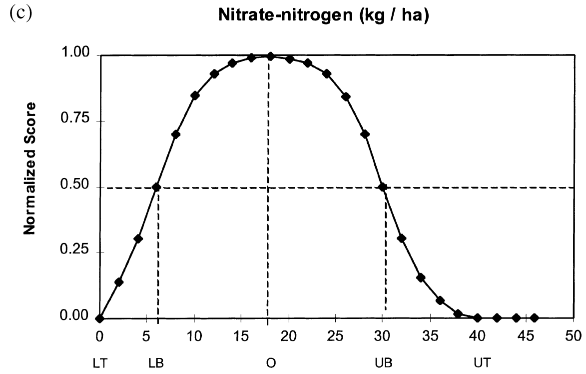
Four 0.14 ha replicate plots for each soil management system were planted in May 1994 in a randomized complete block design on a commercial apple (*Malus domestica* Borkh. ‘Golden Delicious’) orchard in the Yakima Valley of Washington state, USA (latitude 46°30′N). Each plot contains four rows of approximately 80 trees per row trained on a two-wire trellis system. Trees were planted at a spacing of 1.2 m within rows and 3 m between rows for a density of 2240 trees per hectare. The 20 cm of average annual precipitation



(LT = Lower Threshold; LB = Lower Baseline; UT = Upper Threshold)



(LT = Lower Threshold; LB = Lower Baseline; UT = Upper Threshold)



(LT = Lower Threshold; LB = Lower Baseline; O = Optimal; UB = Upper Baseline; UT = Upper Threshold)

Fig. 1. (a) 'More is better' normalized scoring function as applied to aggregate stability. (b) 'Less is better' normalized scoring function as applied to bulk density. (c) 'Optimum' normalized scoring function as applied to NO_3-N.

Table 2
Soil quality score card for the Integrated management treatment

Function	Weight	Score[a]	Value[b]	Indicator Level 1	Weight	Score	Value	Indicator Level 2	Weight	Score	Value
Accommodate water entry	0.25	0.93	0.23	Aggregate stability	0.40	1.00	0.40				
				Bulk density	0.40	0.98	0.39				
				Earthworms	0.20	0.70	0.14				
Facilitate water movement and availability	0.25	0.94	0.24	Water-filled pore space	0.40	0.96	0.39				
				Porosity	0.25	0.99	0.25				
				Organic carbon	0.25	0.96	0.24				
				Earthworms	0.10	0.70	0.07				
Resist surface structure degradation	0.25	0.98	0.24	Aggregate stability	0.40	1.00	0.40				
				Organic carbon	0.40	0.96	0.39				
				Microbial processes	0.20	0.95	0.19	Microbial biomass-C	0.40	0.91	0.36
								Microbial biomass-N	0.40	0.98	0.39
								Water-filled pore space	0.20	0.96	0.19
Sustain fruit quality and productivity	0.25	0.83	0.21	CEC	0.20	0.96	0.19				
				Organic carbon	0.20	0.96	0.19				
				pH	0.10	1.00	0.10				
				Microbial processes	0.10	0.95	0.09	Microbial biomass-C	0.40	0.89	0.35
								Microbial biomass-N	0.40	0.99	0.40
								Water-filled pore space	0.20	0.96	0.19
				Total nitrogen	0.10	0.99	0.10				
				Nitrate nitrogen	0.10	0.28	0.03				
				Extractable phosphorus	0.10	0.34	0.03				
				Electrical conductivity	0.10	1.00	0.10				
	Overall SQ Score =	0.92									

[a] Function level scores are the sums of associated Level 1 indicator values.

[b] For Level 1 indicators that are determined by Level 2 indicators (i.e. microbial processes), scores are the sums of Level 2 indicator values. Scores for other Level 1 and 2 indicators are determined directly by the scoring curve equation.

at the site is supplemented with an under-tree sprinkler irrigation system.

The soil in the study area is a coarse-loamy, mixed, mesic Xerifluventic Haplocambid (FAO: Haplic Cambisol) formed in slack-water sediments deposited during repeated outburst-flood events occurring throughout the Quaternary Period. Prior to installation of the experimental orchard the site had been in grass pasture which was tilled to a depth of 30 cm in January 1994. Soil samples were taken from each of the designated plots following the planting of trees but prior to implementation of management treatments. Analyses of pertinent soil physical, chemical and biological properties revealed no significant differences between treatments at that time (Hopkins-Clark, 1995).

All samples were taken from the inner two rows of each experimental plot to minimize edge effects, excluding the first 20 trees from each end of these sample rows. Sample areas, therefore, included approximately 80 trees per plot. All samples were collected midway between trees within the tree rows.

3.2. Experimental treatments

In cooperation with the orchard managers, we chose appropriate soil management practices for

Table 3
Conventional, integrated, and organic soil management practices

	Year	Conventional	Integrated	Organic
Soil amendment	1994	$Ca(NO_3)_2$ (185.9 kg/ha)	$Ca(NO_3)_2$ (92.9 kg/ha)	Compost (918.6 kg/ha)
	1994		Compost (459.3 kg/ha)	
	1995	$Ca(NO_3)_2$ (185.9 kg/ha)	$Ca(NO_3)_2$ (92.9 kg/ha)	Compost (918.6 kg/ha)
			Compost (459.3 kg/ha)	
Weed control	1994	Glyphosate	Bark mulch; glyphosate	Bark mulch
	1995	Glyphosate	Glyphosate	Landscape fabric
	1996	Glyphosate	Glyphosate	Landscape fabric
	1997	Glyphosate	Glyphosate	Surface weed cultivator
	1998	Glyphosate; pre-emergence herbicide	Glyphosate	Surface weed cultivator

conventional, integrated, and organic soil management systems (Table 3). Conventional orchard management practices included synthetic soil and foliar fertilizer applications and chemical control of weeds and pests. Consistent with modern conventional practices, pheromone-mating disruption was also used to control codling moth (*Cydia pomonella*) in the conventional plots.

The integrated production system included some practices from the conventional and organic production systems that were deemed to be profitable and environmentally benign. Nutrients for the integrated system were supplied partly as composted poultry manure and partly as synthetic fertilizer (Table 3). Weed management practices included bark mulch and limited herbicide applications. Pest management practices were identical to those of the conventional system.

Organic orchard management practices included bark mulch and landscape fabric for weed control in the first 3 years and cultivation in the 1997 and 1998 growing seasons (Table 3). Nutrients for the organic system were supplied in the form of composted poultry manure and calcium chloride foliar sprays. Organically certified biological controls were used for pest management and included applications of *Bacillus thuringiensis* and pheromone mating disruption. Total soil and foliar nitrogen inputs were maintained as close as possible for all three systems.

3.3. Soil sampling and analyses

Measurements of bulk density and water content were determined from soil cores taken from three sites within each plot from the 0–7.5 and 7.5–15 cm depths in June 1998 4 days after irrigation (Arshad et al., 1996). From samples taken at the same time and locations, percent aggregate stability was determined by the wet sieving method for the surface 7.5 cm (Kemper and Rosenau, 1986). Adjustment for coarse primary particles retained on the 1 mm sieve was unnecessary due to the absence of large sand particles.

Three holes were dug at random sites within sample areas of each experimental plot during the second week of May 1998. Samples from 0–7.5 and 7.5–15 cm depths were collected from each hole within an experimental plot and bulked for determination of total nitrogen (Bremner and Mulvaney, 1982), nitrate-nitrogen (Keeney and Nelson, 1982), extractable phosphorus (Olsen and Sommers, 1982), CEC (Rhoades, 1982a), pH (McLean, 1982), and EC (Rhoades, 1982b) by a commercial laboratory (Soil-test Farm Consultants, Moses Lake, Washington). Analyses are reported on a volumetric basis.

Samples for analysis of soil organic carbon (SOC) content and MBC and MBN were collected as for chemical analyses. Organic carbon content was determined by the potassium dichromate method (Nelson and Sommers, 1982). Microbial biomass determinations were made using the chloroform fumigation incubation method (Horwath and Paul, 1994). Earthworm populations were determined by hand-sorting three, 15 cm diameter cores taken from the surface 15 cm in each experimental plot. Prior investigation deeper into the soil profile indicated that earthworms were primarily in the surface 15 cm of soil.

3.4. Soil quality index

The soil quality index proposed by Karlen et al. (1994a, b) for assessing grain production systems was modified in this study to more appropriately reflect cultural requirements of apple orchards. Consistent with Karlen et al. (1994a, b), soil quality was evaluated in terms of four soil functions: (1) accommodating water entry, (2) accommodating water movement and availability, (3) resisting surface structure degradation, and (4) supporting fruit quality and productivity. All four soil functions were assumed to be equally important in this assessment and assigned weights of 0.25. A framework (Table 1) was then developed relating the specific soil quality indicators analyzed in this study to the four soil functions. Numerical weights were assigned to surface soil quality indicators based on their importance to the soil function under consideration.

Aggregate stability, bulk density, and earthworm numbers were deemed important Level 1 indicators of the soil's ability to accommodate water entry for prolonged periods during high-intensity rainfall and frequent irrigation events (Table 1). Stable soil aggregates ensure resistance to the disruptive impact of water drops during rainfall and irrigation (Arshad et al., 1996). Low bulk densities indicate a high volume of pore space necessary for accommodating high volumes of water. Number of earthworms can indicate the extent of macropores (earthworm burrows) able to quickly drain surface water (Karlen et al., 1994a). Due to the beneficial effects of permanent grass cover on many soil physical, chemical, and biological properties (Anderson and Coleman, 1985), grass pasture areas adjacent to the orchard provided optimal values for aggregate stability and bulk density (Table 4). Although soil conditions under orchard management may be quite different than under grass pasture,

Table 4
Scoring function values and references for evaluating soil quality

Scoring curve	Indicator	Depth (cm)	Lower threshold	Upper threshold	Lower baseline	Upper baseline	Optimum	Slope at baseline	Source of threshold/ baseline values
Physical properties									
Less is better	Bulk density (g/cm^3)	0–7.5	1.0	2.0	1.5			−2.617	grass pasture / Brady and Weil, 1999
		0–15							
More is better	Aggregate stability (% 1–2 mm diam.)	0–7.5	0	17	8.5			0.1538	grass pasture
Optimum	Water-filled pore space (%)	0–15	15	105	30	90	60	0.0398	Linn and Doran, 1984; Karlen et al., 1994a, b
Optimum	Porosity (%)	0–15	20	80	40	60	50	0.1280	Karlen et al., 1994a, b
Chemical properties									
More is better	Total nitrogen (kg/ha)	0–15	0	3000	1500			0.009	grass pasture
Optimum	Nitrate-nitrogen (kg/ha)	0–15	0	40	6	30	16	0.104	grass pasture/ Greenham, 1980
Optimum	Extractable Phosphorus (kg/ha)	0–15	10	120	35	95	65	0.0428	grass pasture/ Westwood, 1993
More is better	Cation exchange Capacity (meq/100 g)	0–15	0	21	10.5			0.1159	grass pasture
Optimum	pH	0–15	4.5	9.5	6.5	7.7	5.3	1.3012	Karlen et al., 1994a, b
Optimum	Electrical conductivity (dS/m)	0–15	0	2.0	0.25	1.75	1.0	2.2341	Brady and Weil, 1999; Smith and Doran, 1996
Biological properties									
More is better	Organic carbon (Mg/ha)	0–7.5	0	18.0	9.0			0.0014	grass pasture
		0–15	0	29.0	14.5			0.009	
More is better	Microbial biomass carbon (kg/ha)	0–7.5	0	250	125			0.0109	grass pasture
		0–15	0	375	188			0.0066	
More is better	Microbial biomass nitrogen (kg/ha)	0–7.5	0	75	38			0.0342	grass pasture
		0–15	0	100	50			0.0261	
More is better	Earthworms ($\#/m^2$)	0–15	0	200	100			0.0126	Integrated plots/ Werner, 1996

permanent grass pasture would likely sponsor the best soil physical conditions in terms of water management and environmental filtering for the study site (McLaren and Cameron, 1990). Baseline and threshold values for earthworms were determined from population counts in the orchard and from reported numbers found in other orchards (Werner, 1996).

Although measurement of infiltration rates would provide a more direct assessment of this soil function, infiltration measurements are labor intensive and, therefore, were limited to only a part of the research area. Also, the ponded infiltration rates measured in this study may not accurately reproduce the physical disruption of surface aggregates that occurs during prolonged irrigation or precipitation events. Therefore, infiltration rates were not used in our soil quality index.

Water-filled pore space, porosity, SOC, and earthworm numbers were used as Level 1 indicators to evaluate water movement and availability characteristics (Table 1). Water-filled pore space measurements reflect the in situ water holding ability of the soils under each management system's particular vegetative cover and soil management program. Critical values for water-filled pore space and porosity (Table 4) were taken from Karlen et al. (1994a, b). Pasture areas provided the necessary critical values for SOC.

Aggregate stability, SOC, and microbial processes in the surface layer were deemed important Level 1 indicators of the soil's ability to resist structural degradation (Table 1). Pasture areas provided critical values for aggregate stability and SOC content (Table 4). Microbial processes help develop and maintain soil aggregates and structure and, therefore, contribute to a soil's resistance to physical degradation (Tisdall and Oades, 1982). Microbial processes were further broken down to the second level indicators of MBC, MBN, and water-filled pore space. Linn and Doran (1984) found water-filled pore space to be a good indicator of aerobic microbial activity with maximum activity at 60% saturation. Pasture areas provided critical values for MBC and MBN.

The soil function of sustaining fruit quality and productivity was simplified from the framework suggested by Karlen et al. (1994a, b) for the soil function of supporting plant growth. CEC, SOC, pH, microbial processes, total nitrogen content, nitrate-nitrogen content, extractable phosphorus content, and EC were used as Level 1 indicators for this function (Table 1). Grass pasture areas were used to determine critical values for CEC (Table 4). Optimal and threshold pH values were based upon those used by Karlen et al. (1994a).

Microbial processes may greatly affect the storage and transformation of soil nutrients (Rice et al., 1996; Dalal, 1998). The ability of each soil system to store and cycle nutrients was evaluated in terms of MBC, MBN, and water-filled pore space. As stated earlier, water-filled pore space greatly influences the level of microbial activity and thus nutrient cycling (Linn and Doran, 1984).

Determining critical values for soil nitrogen is difficult due to differences in nitrogen requirements of apple trees throughout the season (Millard, 1995). Both total nitrogen and nitrate-nitrogen contents were used to evaluate adequate nutritional levels and environmentally sound levels of soil nitrogen. Total nitrogen content, largely in the form of organic nitrogen that is gradually made available through mineralization processes, is important in supplying the small amounts of nitrogen needed by fruit trees throughout the season (Greenham, 1980). Although nitrate-nitrogen is an available form of nitrogen, amounts of nitrate-nitrogen greater than necessary for adequate plant growth and productivity may lead to both poor fruit quality (Bramlage et al., 1980) and environmental problems (Doran et al., 1996). Critical values for total nitrogen were determined from adjacent pasture areas (Table 4). Values for nitrate-nitrogen were based on adjacent pasture areas and reported nitrogen requirements of apple trees (Greenham, 1980).

Phosphorus also plays a critical role in tree growth and fruit productivity (Shear, 1980; Westwood, 1993) (Table 4). At high levels, however, it may interfere with the uptake of calcium by trees (Shear, 1980) and be more susceptible to loss in surface water runoff (Sharpley et al., 1996). A lower baseline value for phosphorus was inferred from reported minimal amounts required annually by mature apple trees (Westwood, 1993) and an optimal value was based on levels measured in grass-pasture areas. Our optimal value of 65 kg/ha-15 cm is slightly higher than the 60 kg/ha-20 cm suggested by Doran and Parkin (1996) as an 'environmentally sound' level.

Although apple trees are salt-sensitive plants (Peryea, 1990; Brady and Weil, 1999), information

Table 5
Relative importance of soil properties in the soil quality index

Soil property	Weight[a]	Soil functions effected
Soil organic carbon	0.2125	Accommodate water entry Facilitate water movement and availability Resist surface structure degradation Sustain fruit quality and productivity
Aggregate stability	0.2000	Accommodate water entry Resist surface structure degradation
Water-filled pore space	0.1150	Facilitate water movement and availability Resist surface structure degradation Sustain fruit quality and productivity
Bulk density	0.1000	Accommodate water entry
Earthworms	0.0750	Accommodate water entry Facilitate water movement and availability
Porosity	0.0625	Facilitate water movement and availability
Cation exchange capacity	0.0500	Sustain fruit quality and productivity
Microbial biomass carbon	0.0300	Resist surface structure degradation Sustain fruit quality and productivity
Microbial biomass nitrogen	0.0300	Resist surface structure degradation Sustain fruit quality and productivity
Total nitrogen	0.0250	Sustain fruit quality and productivity
Nitrate-nitrogen	0.0250	Sustain fruit quality and productivity
Extractable phosphorus	0.0250	Sustain fruit quality and productivity
Electrical conductivity	0.0250	Sustain fruit quality and productivity
pH	0.0250	Sustain fruit quality and productivity
Total	1.0000	

[a] Total weights (as a fraction) for all four functions given in Table 2. Table 6

on specific growth and productivity responses to salt concentrations is not well documented. Their growth may be inhibited by EC's well below 4 dS/m, which is the upper-threshold used here and the typical lower limit for soils defined as saline (Brady and Weil, 1999) (Table 4). Research (Peryea, 1990) suggests that apple trees perform optimally at EC levels around 1 dS/m, the optimal value used in this study.

Although the framework of the soil quality index has been discussed in terms of the four soil functions, the weights for each soil property from all four functions have also been totalled to provide an idea of each property's total influence within this particular soil quality index (Table 5). Soil organic carbon and aggregate stability have the greatest influence of any soil properties, together accounting for about 41% of the weight of the index. Physical properties, such as topsoil depth and texture, critical to long-term assessment of soil quality, were not utilized in this index because of the uniformity of soil type and depth across the study site. Besides nitrogen and phosphorus, other essential plant nutrients were not used in this index because of their adequate soil levels (data not shown) and the low environmental risk posed by their presence at the study site.

3.5. *Statistical analyses*

All values were scored and entered on a rating sheet of a spreadsheet computer software package. Soil property measurements and soil quality scores for treatments were statistically analyzed using PROC GLM for a randomized complete block design (SAS Institute, 1996). Requirements of the statistical tests for normal data distribution were fulfilled. Tukey's HSD mean separation procedures were used to determine differences at the 0.05 and 0.1 levels of significance. Unless otherwise noted, significant differences are discussed in terms of the 5% level of probability.

4. Results and discussion

4.1. Physical properties

Soil bulk densities were significantly lower at both the 0–7.5 and 7.5–15 cm depths in the organic plots than in the integrated ($p \leq 0.1$) and conventional plots ($p \leq 0.05$), which were not different from one another at either depth (Table 6). Swezey et al. (1998) similarly measured lower soil bulk densities in organic apple orchard plots utilizing composted amendments as compared to conventional plots. The lower bulk densities measured in organic plots of this study are likely due not only to the addition of compost in 1995 but also to tillage in the 1997 and 1998 growing seasons.

Aggregate stability was low for all treatments, although integrated plots had a significantly higher percentage of stable aggregates than the conventional plots (Table 6). Aggregate stability in organic plots was not significantly different from either integrated or conventional plots. The addition of compost to the integrated plots likely explains the improved aggregate stability over the conventional plots (Tisdall and Oades, 1982). Although organic plots received twice the amount of compost as integrated plots, detrimental effects of tillage may have offset the beneficial effects of organic matter additions (Karlen et al., 1994b).

Water-filled pore space 4 days after irrigation was greater in the integrated plots than in the organic plots; water-filled pore space in conventionally managed plots was not significantly different than in the integrated or the organic plots (Table 6). The higher water-holding capacity of integrated plots as compared to organic plots may have been due to the protective cover of moss in the integrated plots and the greater weed growth in the organic plots.

4.2. Chemical properties

Total nitrogen contents were not significantly different for any of the treatments in the surface 7.5 cm of soil (Table 7). Higher total nitrogen in the 7.5–15 cm layer was measured in integrated plots than in plots of the other two treatments. This higher total nitrogen content in integrated plots coincided with significantly higher nitrate-nitrogen in the integrated treatment compared to the organic treatment at both depths. Nitrate-nitrogen content in conventional plots was also higher than that in organic plots but only at the lower depth. Since trees under all three management systems tended to be overly vigorous, we may assume that the organically managed trees received adequate available nitrogen. Higher nitrate-nitrogen contents in integrated and conventional plots, especially at the lower depths, indicate a greater potential for leaching of excess nitrate to groundwater sources. Although available soil nitrogen levels may vary over the growing season, spring soil analysis of nitrogen is considered a good indication of nitrogen supply for an orchard (Wehrmann and Scharpf, 1980).

Extractable phosphorus was not significantly different in the surface soil layer among treatments, although integrated plots had significantly higher amounts in the lower depths than either conventional or organic plots (Table 7). No significant differences between treatments were found for CEC or pH at either depth. EC was significantly higher in the integrated plots than in the organic plots at both depths.

Table 6
Effect of management systems on soil physical properties in 1998

	Depth (cm)	Conventional	Integrated	Organic	MSD[a] $_{(0.1)}$	MSD $_{(0.05)}$
Bulk density	0–7.5	1.18 (5)[b]	1.12 (8)	0.93 (11)	0.16	0.20
(Mg/m^3)	7.5–15	1.30 (2)	1.28 (3)	1.22 (4)	0.06	0.07
Porosity	0–7.5	55.5 (4)	58.0 (6)	65.0 (6)	5.87	7.16
(%)	7.5–15	51.0 (2)	51.5 (2)	54.0 (3)	2.22	2.71
Aggregate stability (%)	0–7.5	10.6 (57)	22.8 (22)	13.5 (27)	9.6	11.6
Water-filled pore space (%)	0–5	51.8 (16)	50.3 (12)	41.8 (13)	7.36	8.97

[a] MSD=Minimum Significant Difference as determined by Tukey HSD mean separation procedures.

[b] Values in parentheses indicate percent coefficient of variation of measurements.

Table 7
Effects of management systems on soil chemical properties in 1998

	Depth (cm)	Conventional	Integrated	Organic	MSD[a]$_{(0.1)}$	MSD$_{(0.05)}$
Total nitrogen(kg/ha)	0–7.5	1547 (12)[b]	1802 (12)	1573 (9)	295	360
	7.5–15	1041 (7)	1276 (6)	1070 (11)	143	174
Nitrate-nitrogen (kg/ha)	0–7.5	12.5 (35)	20.3 (27)	7.9 (29)	8.5	10.4
	7.5–15	12.4 (19)	15.8 (24)	5.0 (39)	5.4	6.6
Extractable phosphorus	0–7.5	41.8 (22)	52.3 (15)	45.7 (14)	14.3	17.5
(kg/ha)	7.5–15	33.5 (9)	47.9 (9)	37.0 (18)	8.3	10.1
CEC	0–7.5	17.5 (9)	17.9 (14)			
(meq/100 g)	7.5–15	17.0 (7)	17.2 (12)	18.1 (9)	2.1	2.6
pH	0–7.5	6.65 (9)	6.58 (2)	6.78 (2)	0.56	0.69
	7.5–15	6.45 (10)	6.25 (2)	6.50 (3)	0.76	0.92
Electrical conductivity (dS/m)	0–7.5	0.63 (8)	0.85 (22)	0.50 (16)	0.19	0.23
	7.5–15	0.60 (24)	0.68 (15)	0.45 (13)	0.22	0.26

[a] MSD = Minimum Significant Difference as determined by Tukey HSD mean separation procedures.
[b] Values in parentheses indicate percent coefficient of variation of measurements.

Integrated plots also had higher EC than conventional plots in the surface layer but not in the subsurface layer. No differences were seen in EC between the conventional and the organic plots. Despite the statistically significant differences, no detrimental effects on tree growth or fruit productivity appear to be associated with the higher soil EC of the integrated plots.

4.3. *Biological properties*

The content of MBC in the surface 7.5 cm of soil was significantly higher in the integrated ($p \leq 0.05$) and in the organic plots ($p \leq 0.1$) compared to the conventional plots (Table 8). Similar results have been found in other studies (Gunapala and Scow, 1998; Swezey et al., 1998) comparing soils amended with compost or green manure to conventionally-managed soils. Given that all three systems have similar soil respiration rates (data not shown), the higher MBC levels in the integrated and organic systems could indicate long-term increases in SOC (Powlson and Jenkinson, 1981). Differences in MBC measured in the surface layer, however, were not found in the subsurface layer.

Although Sparling (1992) found the ratio of MBC to SOC to be a more useful parameter for monitoring organic matter dynamics than MBC alone, no differences between treatments for this ratio were observed (ratios not shown). Furthermore, the ratios of MBC to SOC (ranging from 1 to 2%) in the orchard plots were similar to the ratios measured in the adjacent grass pasture.

The content of MBN in the surface 7.5 cm was higher in the integrated plots than in the conventional plots but did not differ from that in organic plots

Table 8
Effects of management systems on soil biological properties in 1998

	Depth (cm)	Conventional	Integrated	Organic	MSD[a]$_{(0.1)}$	MSD$_{(0.05)}$
Microbial biomass carbon	0–7.5	151 (12)[b]	195 (5)	177 (16)	23.3	28.5
(kg C/ha)	7.5–15	83 (27)	93 (26)	93 (26)	24.8	30.3
Microbial biomass nitrogen	0–7.5	61 (24)	76 (12)	72 (16)	15.6	19.0
(kg N/ha)	7.5–15	25 (32)	32 (25)	32 (16)	9.7	11.8
Organic carbon	0–7.5	13.0 (7)	15.6 (8)	14.9 (8)	2.96	3.61
(Mg/ha)	7.5–15	8.3 (10)	9.7 (7)	9.3 (19)	2.37	2.88
Earthworms (#/m^2)		35 (88)	212 (100)	106 (106)	171	208

[a] MSD=Minimum Significant Difference as determined by Tukey HSD mean separation procedures.
[b] Values in parentheses indicate percent coefficient of variation of measurements.

(Table 8). Conventional plots did not differ from organic plots in terms of MBN content. In the subsurface layer no differences between treatments were observed. Similar amounts of total nitrogen were stored in the form of living biomass in all three systems, ranging from 3.9% in conventional plots to 4.4% in the integrated and the organic plots.

Despite the differences in microbial biomass among treatments, no significant differences were found in SOC contents for the three treatments at either the 0–7.5 or 7.5–15 cm depths for 1998 (Table 8). This agrees with other studies (Rice et al., 1996; Swezey et al., 1998) that found microbial biomass measurements to be more sensitive to management differences than SOC. The 1998 MBC measurements are, however, indicative of the significant increases in SOC in the integrated and the organic plots since 1994 (data not shown). Amounts of SOC in conventional plots, on the other hand, have not changed significantly since 1994.

Data collected from the 1996-growing season following compost applications in 1995 did reflect significantly higher SOC contents in both organic and integrated plots than in conventional plots (data not shown). The lack of measurable differences in SOC between treatments in 1998 is likely due to the large background of SOC present (Powlson and Jenkinson, 1981). When our study was initiated in 1994, SOC levels in our plots were relatively high for orchard soils in the Yakima Valley because of the long history of our study site being used as pasture for a dairy operation.

There were significantly greater numbers of worms in the integrated plots than in the conventional plots ($p \leq 0.1$). Although not statistically significant (due to the large variation in data), the organic plots had more than three times the number of earthworms than the conventional plots. The paucity of earthworms found in conventional plots may have been due to a fall 1997 application of simazine, a pre-emergence herbicide moderately toxic to earthworms (Ernst, 1995) and only applied to conventional plots. Two growing seasons of weed-control tillage in the organic plots (Table 3) likely resulted in their lower earthworm populations than in the integrated plots with no tillage, as has been supported in other studies (Berry and Karlen, 1993).

4.4. Soil quality index ratings

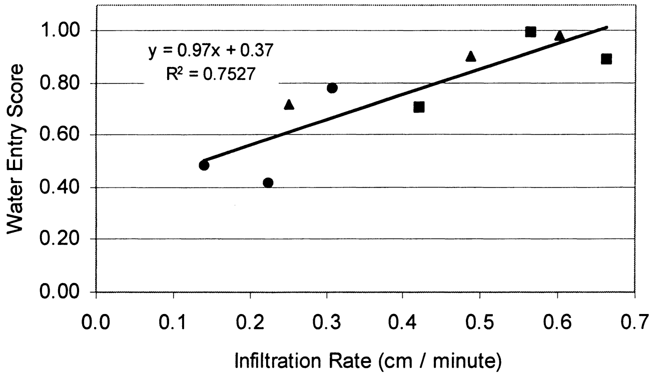
Integration of the normalized soil property values into the soil quality index resulted in the integrated plots receiving a significantly higher score than the conventional plots for their ability to accommodate water entry (Table 9). The much higher aggregate stability of soil under integrated management was largely responsible for these differences. At the $p \leq 0.1$ level of probability, water entry scores for organic plots were also significantly higher than conventional plot scores largely due to lower bulk densities in organic plots. Water entry scores for the integrated and the organic plots were similar. Regression analysis of the scores for water entry and the results of a limited number of ponded, single-ring infiltration tests indicate good correlation ($r^2=0.75$; $p=0.002$) between the index scores for this function and infiltration rates (Fig. 2).

All three treatments scored high in their ability to facilitate water movement and availability (Table 9). This assessment indicates that none of the three management systems have significantly altered the soil's ability to hold and release water from the soil's non-degraded state under permanent grass cover. It also indicates that despite the greater weed growth in the organic plots, there is still sufficient water available for plant growth, fruit production, and microbial activity.

Table 9
Soil quality ratings for management systems in 1998

Treatment	Conventional	Integrated	Organic	MSD[a] $_{(0.1)}$	MSD$_{(0.05)}$
Accommodate water entry	0.153	0.235	0.213	0.057	0.070
Facilitate water movement and availability	0.208	0.235	0.205	0.025	0.031
Resist surface structure degradation	0.185	0.245	0.225	0.052	0.063
Sustain fruit quality and productivity	0.225	0.213	0.238	0.016	0.019
Total	0.783	0.923	0.878	0.099	0.121

[a] MSD=Minimum Significant Difference as determined by Tukey HSD mean separation procedures.



(● = conventional treatment; ▲ = integrated treatment; ■ = organic treatment; solid line = regression line for all observations)

Fig. 2. Observed and predicted soil quality scores for accommodating water entry in relation to a limited number of ponded infiltration measurements.

Soils in integrated plots exhibited significantly ($p \leq 0.1$) greater resistance to physical degradation than conventional plots (Table 9). The effects of the organic treatment on the soil's ability to resist degradation did not result in a significantly different score from either of the other two treatments, however. Differences in treatment scores for this soil function were due to greater aggregate stability, greater numbers of earthworms, and higher microbial biomass in the integrated plots.

For the function of sustaining fruit quality and productivity, the organic plots scored higher than integrated plots largely due to excessive levels of nitrate and phosphorus in the rooting zone of integrated plots (Table 9). Scoring curves in this category were designed to take into account the belief that fruit quality and productivity cannot be sustained at the expense of overall environmental quality. Scores for conventionally managed plots were not significantly different from scores for the organic or the integrated plots.

The soil quality index only rates a soil in terms of its potential for fruit yield and quality while taking into account environmental concerns such as excessive nitrate levels. In apple orchards, many other production practices not related to soil properties, such as pruning and thinning practices, contribute to yield and quality. Although overall yields in the 1998-growing season were similar for all three management systems, organic apples were smaller than either the integrated or conventional apples and had the highest cullage rate (Table 10). The use of chemical fruit thinning sprays in the integrated and conventional plots likely resulted in their smaller but higher quality fruit yields in comparison to yields in organic plots where fruit were only hand thinned. Thus, the use of harvest data for validation of this soil function is not necessarily appropriate given different fruit thinning practices, such as chemical versus hand thinning.

Table 10
Yields, fruit size, and cullage for management systems in 1998

	Conventional	Integrated	Organic
Yield (Mg/ha)	66a[a]	64a	72a
Fruit size (kg/apple)	0.23a	0.23a	0.18a
Culls (% of yield)	57b	63ab	70a

[a] Values in rows with the same letter are not different at the 0.05 level of significance using Tukey's HSD mean separation procedures.

Although all three management systems received high total soil quality scores, the integrated system scored significantly higher than the conventional system (Table 9). A score of 1.0 would indicate that ideal soil conditions have been maintained for both optimal apple production and for optimal environmental quality. The score of 0.92 for integrated management indicates that while some effects of this system on soil quality are not ideal, they are overall better than the conventional system, which received a score of 0.78. The 0.88 score for the organic treatment was not significantly different than scores for the other two systems.

Appropriate interpretation of these overall soil quality scores requires a full soil quality report which includes the score card as well as the scoring function parameters and information sources used to determine parameter values. For example, a soil quality report for the integrated treatment would consist of Tables 2 and 4. Together, these two tables provide detailed information on the relationship of each soil property to overall soil quality and, more importantly, how that relationship was defined. Agricultural consultants, farm advisors, researchers, and growers can use such a soil quality report to make management decisions, interpret field observations, and to more fully evaluate laboratory results.

5. Summary and conclusions

In comparing the effects of conventional, integrated, and organic management practices on soil properties in apple orchards, significant differences were observed in the fourth year after planting. Increased aggregate stability, microbial biomass, and earthworm abundance were associated with improved soil quality under integrated management when compared to conventional management. Organic management resulted in lower bulk densities and generally improved biological properties compared to conventional management. Few differences in soil properties were measured between the integrated and organic systems.

When selected physical, chemical, and biological soil properties were integrated into a soil quality index, the integrated production system received a significantly higher soil quality rating (0.92) than did the conventional production system (0.78). The organic production system did not result in a significantly different soil quality rating (0.88) than the two other management systems. Soil quality under organic management would likely have been higher, if not for the tillage operations in the last two growing seasons.

The results of this study indicated that the soil quality index employed provides an effective framework for evaluating the overall effects of different orchard production practices on soil quality. Although the soil quality index demonstrated in this study utilized information collected within a rather narrow timeframe, it could easily be used to more fully assess soil-quality dynamics within a single season or throughout the course of several seasons. For example, further evaluations of and adjustments to this soil quality index may be made in future growing seasons to fulfill the goals of monitoring soil quality changes over time and to refine the index. The flexibility of this approach through adjustment of the numerical weighting of soil functions and parameters allows for its application to different regions and cropping systems and for different assessment purposes.

Although integration of soil properties into a soil quality index relies in part on the assessor's judgment, the formal framework provided by the index offers a systematic format for consistent evaluation. A soil quality report generated by the development of a soil quality index is readily usable by consultants, farm advisors, researchers, and growers wanting to monitor changes in soil quality. Monitoring and interpreting the dynamics of soil environments as they are affected by intensive production practices will be crucial to maintaining long-term soil quality. A soil quality index is a quantifiable method for achieving this goal.

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