Environmental, Energetic, and Economic Comparisons of Organic and Conventional Farming Systems

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Various organic technologies have been utilized for about 6000 years to make agriculture sustainable while conserving soil, water, energy, and biological resources. Among the benefits of organic technologies are higher soil organic matter and nitrogen, lower fossil energy inputs, yields similar to those of conventional systems, and conservation of soil moisture and water resources (especially advantageous under drought conditions). Conventional agriculture can be made more sustainable and ecologically sound by adopting traditional organic farming technologies.

Keywords: organic, agriculture, conventional

Heavy agricultural reliance on synthetic chemical fertilizers and pesticides is having serious impacts on public health and the environment (Pimentel et al. 2005). For example, more than 90% of US corn farmers rely on herbicides for weed control (Pimentel et al. 1993), and one of the most widely used of those herbicides, atrazine, is also one of the most commonly found pesticides in streams and groundwater (USGS 2001). The estimated environmental and health care costs of pesticide use at recommended levels in the United States run about $12 billion every year (Pimentel 2005).

Other aspects of conventional agriculture also have adverse effects on environmental and human health, as well as a high price tag. Nutrients from fertilizer and animal manure have been associated with the deterioration of some large fisheries in North America (Frankenberger and Turco 2003), and runoff of soil and nitrogen fertilizer from agricultural production in the Corn Belt has contributed to the "dead zone" in the Gulf of Mexico. The National Research Council (BANR/NRC 2003) reports that the cost of excessive fertilizer use—that is, fertilizer inputs that exceed the amount crops can use—is $2.5 billion per year. Modern agricultural practices can also contribute to the erosion of soil. The estimated annual costs of public and environmental health losses related to soil erosion exceed $45 billion (Pimentel et. al. 1995).

Integrated pest and nutrient management systems and certified organic agriculture can reduce reliance on agrochemical inputs as well as make agriculture environmentally and economically sound. Pimentel and Pimentel (1996) and the National Research Council (BANR/NRC 2003) have demonstrated that sound management practices can reduce pesticide inputs while maintaining high crop yields and improving farm economics. Some government programs in Sweden, Canada, and Indonesia have demonstrated that pesticide use can be reduced by 50% to 65% without sacrificing high crop yields and quality (BANR/NRC 2003).

The aim of organic agriculture is to augment ecological processes that foster plant nutrition yet conserve soil and water resources. Organic systems eliminate agrochemicals and reduce other external inputs to improve the environment and farm economics. The National Organic Program (a program of the USDA Agricultural Marketing Service; 7 CFR pt. 205 [2002]) codifies organic production methods that are based on certified practices verified by independent third-party reviewers. These systems give consumers assurance of how their food is produced and enable consumers to choose foods on the basis of the methods by which they were produced. The

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National Organic Standards Program prohibits the use of synthetic chemicals, genetically modified organisms, and sewage sludge in organically certified production.

Organic agriculture is a fast-growing agricultural section in the United States. Dimitri and Greene (2002) report a doubling of area in organic production from 1992 to 1997, currently on more than 500,000 hectares (ha). Organic food sales total more than $7 billion per year and are growing at double-digit rates (Greene 2000, 2004, ERS 2003). With continuing consumer concerns about the environment and the chemicals used in food production, and with the growing availability of certified organic production, the outlook for continuing growth of organic production is bright (Dimitri and Greene 2002).

Since 1981, the Rodale Institute Farming Systems Trial (FST) has compared organic and conventional grain-based farming systems. The results presented here represent a 22-year study of these farming systems, based on environmental impacts, economic feasibility, energetic efficiency, soil quality, and other performance criteria. The information from this trial can be a tool for developing agricultural policies more in tune with the environment while increasing energy efficiency and economic returns.

The Rodale Institute Farming Systems Trial

From 1981 through 2002, field investigations were conducted at the Rodale Institute FST in Kutztown, Pennsylvania, on 6.1 ha. The soil at the study site is a moderately well-drained Comly silt loam. The growing climate is subhumid temperate (average temperature is 12.4 degrees Celsius and average rainfall is 1105 millimeters [mm] per year).

The experimental design included three cropping systems (main plots). These systems, detailed below, included (a) conventional, (b) animal manure and legume-based organic (hereafter organic animal-based), and (c) legume-based organic systems. The main plots were 18 × 92 meters (m), and these were split into three 6 × 92 m subplots, which allowed for same-crop comparisons in any one year. The main plots were separated with a 1.5-m grass strip to minimize cross movement of soil, fertilizers, and pesticides. The subplots were large enough that farm-scale equipment could be used for operations and harvesting. Each of the three cropping systems was replicated eight times.

Conventional cropping. The conventional cropping system, based on synthetic fertilizer and herbicide use, represented a typical cash-grain, row-crop farming unit and used a simple 5-year crop rotation (corn, corn, soybeans, corn, soybeans) that reflects commercial conventional operations in the region and throughout the Midwest (more than 40 million ha are in this production system in North America; USDA 2003). Fertilizer and pesticide applications for corn and soybeans followed Pennsylvania State University Cooperative Extension recommendations. Crop residues were left on the surface of the land to conserve soil and water resources. Thus, during the growing season, the conventional system had no more exposed soil than in either the organic animal-based or the organic legume-based systems. However, it did not have cover crops during the nongrowing season.

Organic animal-based cropping. This system represented a typical livestock operation in which grain crops were grown for animal feed, not cash sale. This rotation was more complex than the rotation used in the conventional system. The grain-rotation system included corn, soybeans, corn silage, wheat, and red clover–alfalfa hay, as well as a rye cover crop before corn silage and soybeans.

Aged cattle manure served as the nitrogen source and was applied at a rate of 5.6 metric tons (t) per ha (dry), 2 years out of every 5, immediately before plowing the soil for corn. Additional nitrogen was supplied by the plow-down of legume–hay crops. The total nitrogen applied per hectare with the combined sources was about 40 kilograms (kg) per year (or 198 kg per ha for any given year with a corn crop). The system did not use herbicides for weed control; it relied instead on mechanical cultivation, weed-suppressing crop rotations, and relay cropping, in which one crop acted as a living mulch for another.

Organic legume-based cropping. This system represented a cash grain operation, without livestock. Like the conventional system, it produced a cash grain crop every year; however, it used no commercial synthetic fertilizers, relying instead on nitrogen-fixing green manure crops as the nitrogen source. The final rotation system included hairy vetch (winter cover crop used as a green manure), corn, rye (winter cover crop), soybeans, and winter wheat. The hairy vetch winter cover crop was incorporated before corn planting as a green manure. The initial 5-year crop rotation in the legume-based system was modified twice to improve the rotation. The total nitrogen added to this system per ha per year averaged 49 kg (or 140 kg per ha for any given year with a corn crop). Both organic systems (animal based and legume based) included a small grain, such as wheat, grown alone or interseeded with a legume. Weed control practices were similar in both organic systems, neither of which used herbicides for weed control.

Measurements recorded in the experimental treatments

Cover crop biomass, crop biomass, weed biomass, grain yields, nitrate leaching, herbicide leaching, percolated water volumes, soil carbon, soil nitrogen, and soil water content were measured in all systems. In addition, seasonal total rainfall, energy inputs and returns, and economic inputs and returns were determined.

A lysimeter, a steel cylinder 76 centimeters (cm) long by 76 cm in diameter, was installed in four of the eight replications in each cropping system in fall 1990 to enable the collection of percolated water. The top of each lysimeter was approximately 36 cm below the soil surface to allow normal field operations to be carried out directly over the lysimeters. Water

could not escape from the lysimeter system, and leachate samples were collected throughout the year.

Levels of nitrogen as nitrate in leachate samples were determined by the Soil and Plant Nutrient Laboratory at Michigan State University in East Lansing. Herbicides in leachate samples were analyzed by M. J. Reider Associates, Reading, Pennsylvania. Total soil carbon and nitrogen were determined by the Agricultural Analytical Services Laboratory at Pennsylvania State University in University Park. Soil water content was determined gravimetrically on sieved soil (particles 2 mm in diameter). Statistical analyses were carried out using SPSS version 10.1.3 General Linear Model Univariate Analysis of Variance.

Results

We examined the data from the 22-year experiments carried out at the Rodale Institute, which compared the organic animal-based, organic legume-based, and conventional systems. The following data were considered for all three systems: crop yields for corn and soybeans, impacts of drought on crop yields, fossil energy requirements, economic costs and benefits, soil carbon (organic matter) changes over time, and nitrogen accumulation and nitrate leaching.

Crop yields under normal rainfall. For the first 5 years of the experiment (1981–1985), corn grain yields averaged 4222, 4743, and 5903 kg per ha for the organic animal, organic legume, and conventional systems, respectively, with the yields for the conventional system being significantly higher than for the two organic systems. After this transition period, corn grain yields were similar for all systems: 6431, 6368, and 6553 kg per ha for the organic animal, organic legume, and conventional systems, respectively (Pimentel et al. 2005). Overall, soybean yields from 1981 through 2001 were 2461, 2235, and 2546 kg per ha for the organic animal, organic legume, and conventional systems, respectively (Pimentel et al. 2005). The lower yield for the organic legume system is attributable to the failure of the soybean crop in 1988, when climate conditions were too dry to support relay intercropping of barley and soybeans. If 1988 is taken out of the analysis, soybean yields are similar for all systems.

Crop yields under drought conditions. The 10-year period from 1988 to 1998 had 5 years in which the total rainfall from April to August was less than 350 mm (compared with 500 mm in average years). Average corn yields in those 5 dry years were significantly higher (28% to 34%) in the two organic systems: 6938 and 7235 kg per ha in the organic animal and the organic legume systems, respectively, compared with 5333 kg per ha in the conventional system. During the dry years, the two organic systems were not statistically different from each other in terms of corn yields.

During the extreme drought of 1999 (total rainfall between April and August was only 224 mm compared with the normal average of 500 mm), the organic animal system had significantly higher corn yields (1511 kg per ha) than either the organic legume (421 kg per ha) or the conventional system (1100 kg per ha). Crop yields in the organic legume system were much lower in 1999 because the high biomass of the hairy vetch winter cover crop used up a large amount of the soil water (Lotter et al. 2003).

Soybean yields responded differently than the corn during the 1999 drought. Specifically, soybean yields were about 1800, 1400, and 900 kg per ha for the organic legume, the organic animal, and the conventional systems, respectively. These treatments were significantly different ($p = 0.05$) from each other (Pimentel et al. 2005).

Over a 12-year period, water volumes percolating through each system (collected in lysimeters) were 15% and 20% higher in the organic legume and organic animal systems, respectively, than in the conventional system. This indicated an increased groundwater recharge and reduced runoff in the organic systems compared with the conventional system. During the growing seasons of 1995, 1996, 1998, and 1999, soil water content was measured for the organic legume and conventional systems. The measurements showed significantly more water in the soil farmed using the organic legume system than in the conventional system (Pimentel et al. 2005). This accounted for the higher soybean yields in the organic legume system in 1999 (Pimentel et al. 2005).

Energy inputs. The energy inputs in the organic animal, organic legume, and conventional corn production systems were assessed. The inputs included fossil fuels for farm machinery, fertilizers, seeds, and herbicides. About 5.2 million kilocalories (kcal) of energy per ha were invested in the production of corn in the conventional system. The energy inputs for the organic animal and organic legume systems were 28% and 32% less than those of the conventional system, respectively (figure 1). Commercial fertilizers for the conventional system were produced employing fossil energy, whereas the nitrogen nutrients for the organic systems were obtained from legumes or cattle manure, or both. The intensive reliance on fossil fuel energy in the conventional corn production system is why that system requires more overall energy inputs than do organic production systems. Fossil energy inputs were also required to transport and apply the manure to the field.

The energy inputs for soybean production in the organic animal, organic legume, and conventional systems were similar: 2.3 million kcal, 2.3 million kcal, and 2.1 million kcal per ha, respectively (figure 1).

Economics. Two economic studies of the FST were completed, evaluating its first 9 years (Hanson et al. 1990) and first 15 years of operation (Hanson et al. 1997). These two studies captured the experiences of organic farmers as they develop over time a rotation that best fits their farm. With the development of the final rotation, a third evaluation was completed comparing this rotation with its conventional alternative (Hanson and Musser 2003). Many organic grain farmers in the mid-Atlantic region have been adopting this "Rodale

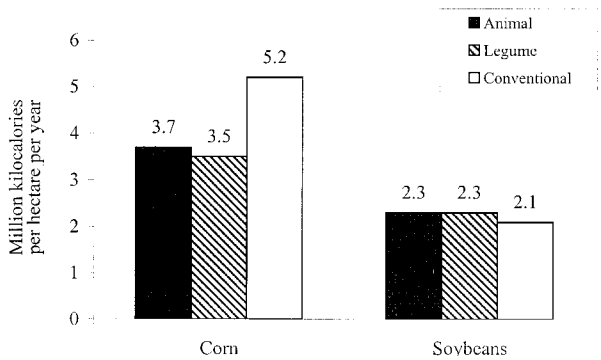

Figure 1. Average energy inputs for corn and soybeans (in millions of kilocalories per hectare per year) in the three systems used in the Rodale Institute Farming Systems Trial from 1991 to 2000: organic animal-based cropping, organic legume-based cropping, and conventional cropping.

rotation" on their farms, and there was strong interest in an economic evaluation of this rotation alone (i.e., without the transition period or learning curve).

The third economic comparison of the organic corn–soybean rotation and conventional corn–soybean systems covered the period 1991 to 2001 (figure 2). Without price premiums for the organic rotation, the net returns for both rotations were similar. The annual net return for the conventional system averaged about $184 per ha, while the organic legume system for cash grain production averaged $176 per ha. The annual costs per ha for the conventional versus organic rotations, respectively, were (a) seed, $73 versus $103; (b) fertilizers and lime, $79 versus $18; (c) pesticides, $76 versus $0; (d) machinery costs, $117 versus $154;

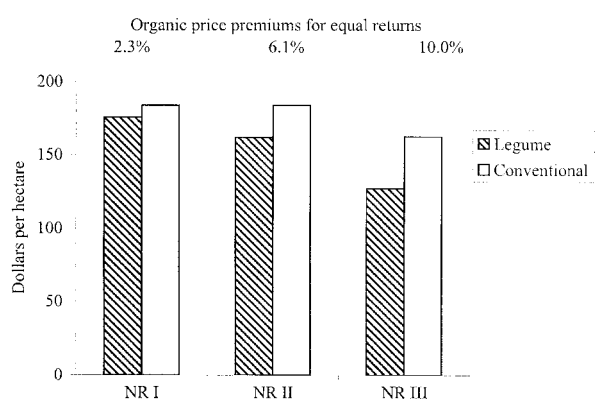

Figure 2. Average net returns per hectare (ha) for a 400-ha farm for the organic legume and conventional grain rotations in the Rodale Institute Farming Systems Trial from 1991 to 2001. NR I = revenue minus explicit costs; NR II = NR I minus transitional costs; NR III = NR II minus all labor costs. Source: Hanson and Musser (2003).

and (e) hired labor, $9 versus $6. Similar revenue comparisons are $538 per ha and $457 per ha (conventional versus organic). The net returns for the conventional rotation were more variable (i.e., risky). The standard deviation for net returns over the 10-year period was $127 for the conventional rotation and $109 for the organic rotation.

When the costs of the biological transition for the organic rotation (1982–1984) were included, the net returns for the organic rotation were reduced to $162 per ha, while the conventional net returns remained unchanged. Including the costs of family labor for both rotations reduced the net returns of conventional farming to $162 and organic farming to $127. However, even with the inclusion of the biological transition and family labor costs, the organic price premium required to equalize the organic and conventional returns was only 10% above the conventional product. Throughout the 1990s, the organic price premium for grains has exceeded this level, and premiums now range between 65% and 140% (New Farm Organization 2003).

The organic system requires 35% more labor, but because it is spread out over the growing season, the hired labor costs per ha are about equal between the two systems. Each system was allowed 250 hours of "free" family labor per month. When labor requirements exceeded this level, labor was hired at $13 per hour. With the organic system, the farmer was busy throughout the summer with the wheat crop, hairy vetch cover crop, and mechanical weed control (but worked less than 250 hours per month). In contrast, the conventional farmer had large labor requirements in the spring and fall, planting and harvesting, but little in the summer months. This may have implications for the growing number of part-time farmers for whom the availability of family farm labor is severely limited. Other organic systems have been shown to require more labor per hectare than conventional crop production. On average, organic systems require about 15% more labor (Sorby 2002, Granatstein 2003), but the increase in labor input may range from 7% (Brumfield et al. 2000) to a high of 75% (Karlen et al. 1995, Nguyen and Haynes 1995).

Over the 10-year period, organic corn (without price premiums) was 25% more profitable than conventional corn ($221 per ha versus $178 per ha). This was possible because organic corn yields were only 3% less than conventional yields (5843 kg per ha versus 6011 kg per ha), while costs were 15% less ($351 per ha versus $412 per ha). However, the organic grain rotation required a legume cover crop before the corn. This was established after the wheat harvest. Thus, corn was grown 60% of the time in the conventional rotation, but only 33% of the time in the organic rotation. Stated in another way, the yields per ha between organic and conventional corn for grain may be similar within a given year; however, overall production of organic corn is diminished over a multiple-year period because it is grown less frequently. On the other hand, the reduced amount of corn grown in the organic rotation is partly compensated for with the additional crop of wheat.

Soil carbon. Soil carbon, which correlates with soil organic matter levels, was measured in 1981 and 2002 (figure 3). In 1981, soil carbon levels were not different ($p = 0.05$) between the three systems. In 2002, however, soil carbon levels in the organic animal and organic legume systems were significantly higher than in the conventional system: 2.5% and 2.4% versus 2.0%, respectively (figure 3). The annual net aboveground carbon input (based on plant biomass and manure) was the same in the organic legume system and the conventional system (about 9000 kg per ha) but close to 12% higher in the organic animal system (about 10,000 kg per ha). However, the two organic systems retained more of that carbon in the soil, resulting in an annual soil carbon increase of 981 and 574 kg per ha in the organic animal and organic legume systems, compared with only 293 kg per ha in the conventional system (calculated on the basis of about 4 million kg per ha of soil in the top 30 cm). The increased carbon was also associated with higher water content of the soils in these systems compared with the conventional system. The higher soil water content in the organic systems accounted for the higher corn and soybean yields in the drought years in these systems compared with the conventional system (Lotter et al. 2003).

Soil nitrogen. Soil nitrogen levels were measured in 1981 and 2002 in the organic animal, organic legume, and conventional systems (figure 3). Initially the three systems had similar percentages of soil nitrogen, or approximately 0.31%. By 2002, the conventional system remained unchanged at 0.31%, while nitrogen levels in the organic animal and organic legume systems significantly increased to 0.35% and 0.33%, respectively. Harris and colleagues (1994) used ^{15}N (nitrogen-15) to demonstrate that 47%, 38%, and 17% of the nitrogen from the organic animal, organic legume, and conventional systems, respectively, was retained in the soil a year after application.

Nitrate leaching. Overall, the concentrations of nitrogen as nitrate in leachates from the farming systems varied between 0 and 28 parts per million (ppm) throughout the year (Pimentel et al. 2005). Leachate concentrations were usually highest in June and July, shortly after applying fertilizer in the conventional systems or plowing down the animal manure and legume cover crop. In all systems, increased soil microbial activity during the growing season appears to have contributed to increased nitrate leaching.

Water leachate samples from the conventional system sometimes exceeded the regulatory limit of 10 ppm for nitrate concentration in drinking water. A total of 20% of the conventional system samples were above the 10-ppm limit, while 10% and 16% of the samples from the organic animal and organic-legume systems, respectively, exceeded the nitrate limit.

Over the 12-year period of monitoring (1991–2002), all three systems leached between 16 and 18 kg of nitrogen as nitrate per ha per year. These rates were low compared with the results from other experiments with similar nitrogen inputs, in which leaching of nitrogen as nitrate ranged from 30 to 146 kg per ha per year (Fox et al. 2001, Power et al. 2001). When measuring these nitrogen losses as a percentage of the nitrogen originally applied to the crops in each system, the organic animal, organic legume, and conventional systems lost about 20%, 32%, and 20%, respectively, of the total nitrogen as nitrate.

The high nitrate leaching in the organic legume system was not steady over the entire period of the study; instead, it occurred sporadically, especially during a few years of extreme weather. For example, in 1995 and 1999, the hairy vetch green manure supplied approximately twice as much nitrogen as needed for the corn crop that followed, contributing excess nitrogen to the soil and making it available for leaching. In 1999, the heavy nitrogen input from hairy vetch was followed by a severe drought that stunted corn growth and reduced the corn's demand for nitrogen. In both years, these nitrogen-rich soils were also subjected to unusually heavy fall and winter rains that leached the excess nitrogen into the lower soil layers. Monitoring of soil nitrogen and cover crop production is needed to manage the potential for excessive nitrate in all systems.

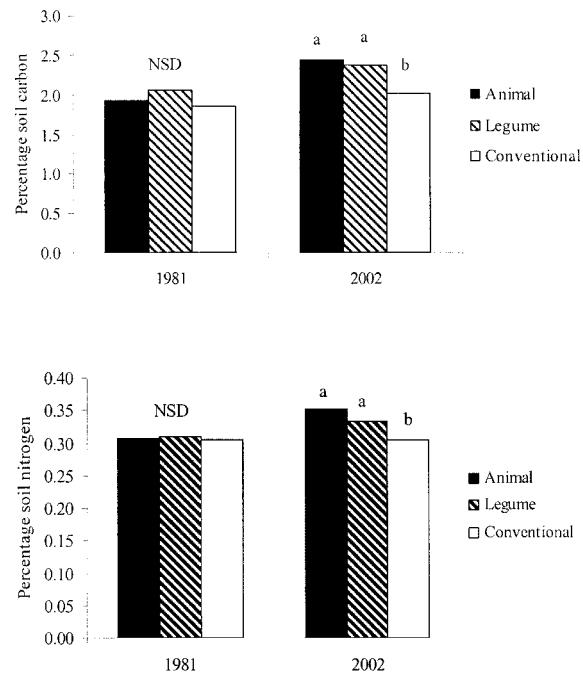

Figure 3. Percentage of soil carbon (above) and nitrogen (below) for the three systems of the Rodale Institute Farming Systems Trial in 1981 and 2002 (organic animal-based cropping, organic legume-based cropping, and conventional cropping). Different letters indicate statistically significant differences according to Duncan's multiple range test; p < 0.05. NSD = not significantly different.

These data contrast with the results of experiments in Denmark, which indicated that nitrogen leaching from the conventional treatments was twice that in the organic agricultural systems (Hansen et al. 2001). Overall, nitrogen leaching levels were lower in the FST rotation study than in those reported by Hansen and others.

Herbicide leaching. Four herbicides were applied in the conventional system: atrazine (to corn), pendimethalin (to corn), metolachlor (to corn and soybeans), and metribuzin (to soybeans). From 2001 to 2003, atrazine and metolachlor were only detected in water leachate samples collected from the conventional system. No metribuzin or pendimethalin were detected after application (Pimentel et al. 2005).

In the conventional plots where corn was planted after corn, and atrazine was applied two years in a row, atrazine in the leachate sometimes exceeded 3 parts per billion (ppb), the maximum contaminant level (MCL) set by the US Environmental Protection Agency (EPA) for drinking water. These atrazine levels were higher than those in the corn-after-soybean treatment (Pimentel et al. 2005). In the conventional system, metolachlor was also detected at 0.2 to 0.6 ppb. When metolachlor was applied two years in a row in a corn-after-corn treatment, it peaked at 3 ppb (Pimentel et al. 2005). The EPA has not yet established an MCL for metolachlor in drinking water.

Soil biology. Among the natural biological processes on which the organic rotations depend is symbiosis of arbuscular mycorrhizae, and this aspect was investigated in the FST experiments. Arbuscular mycorrhizal (AM) fungi are beneficial and indigenous to most soils. They colonize the roots of most crop plants, forming a mutualistic symbiosis (the mycorrhiza). The fungus receives sugars from the root of the host plant, and the plant benefits primarily from enhanced nutrient uptake from the fungus. The extraradical mycelia of the AM fungi act, in effect, as extensions of the root system, more thoroughly exploring the soil for immobile mineral nutrients such as phosphate (Smith and Read 1997). Arbuscular mycorrhizae have been shown to enhance disease resistance, improve water relations, and increase soil aggregation (Miller and Jastrow 1990, Hooker et al. 1994, Wright et al. 1999, Augé 2000). Efficient utilization of this symbiosis contributes to the success of organic production systems.

Soils of the Rodale Institute FST have been sampled to study the impact of conventional and organic agricultural management on indigenous populations of AM fungi. Soils farmed with the two organic systems had greater populations of spores of AM fungi and produced greater colonization of plant roots than in the conventional system (Douds et al. 1993). Most of this difference was ascribed to greater plant cover (70%) on the organic systems compared with the conventional corn–soybean rotation (40%). This was due to overwintering cover crops in the organic rotation (Galvez et al. 1995). In addition to fixing or retaining soil nitrogen, these cover crops provide roots for the AM fungi to colonize and maintain the fungi's viability during the interval from cash crop senescence to next year's planting. Though levels of AM fungi were greater in the organically farmed soils, indices of ecological species diversity were similar in the farming systems (Franke-Snyder et al. 2001).

Wander and colleagues (1994) demonstrated that soil respiration was 50% higher in the organic animal system, compared with the conventional system, 10 years after initiation of the Rodale Institute FST. Microbial activity in the organic soils may be higher than in the conventional system's soils and hence could explain the higher metabolism rates in the organic systems (Lavelle and Spain 2001).

Discussion

The crop yields and economics of organic systems, compared with conventional systems, appear to vary based on the crops, regions, and technologies employed in the studies. However, the environmental benefits attributable to reduced chemical inputs, less soil erosion, water conservation, and improved soil organic matter and biodiversity were consistently greater in the organic systems than in the conventional systems.

Soil organic matter and biodiversity. Soil organic matter provides the base for productive organic farming and sustainable agriculture. After 22 years of separate management, soil carbon (soil organic matter) was significantly higher in both the organic animal and the organic legume systems than in the conventional system. Soil carbon increased 27.9%, 15.1%, and 8.6% in the organic animal, organic legume, and conventional systems, respectively (figure 3).

The amount of organic matter in the upper 15 cm of soil in the organic farming systems was approximately 110,000 kg per ha. The soil of the upper 15 cm weighed about 2.2 million kg per ha. Approximately 41% of the volume of the organic matter in the organic systems consisted of water, compared with only 35% in the conventional systems (Sullivan 2002). The amount of water held in both of the organic systems is estimated at 816,000 liters per ha. The large amount of soil organic matter present in the organic systems aided in making the systems more tolerant of droughts, such as those that occurred in 1999 and other drought years.

Large amounts of biomass (soil organic matter) are expected to significantly increase soil biodiversity (Pimentel et al. 1992, Troeh and Thompson 1993, Lavelle and Spain 2001, Mader et al. 2002). The arthropods per ha can number from two million to five million, and earthworms from one million to five million (Lavelle and Spain 2001, Gray 2003). The microarthropods and earthworms were reported to be twice as abundant in organic versus conventional agricultural systems in Denmark (Hansen et al. 2001). The weight of the earthworms per ha in agricultural soils can range from 2000 to 4000 kg (Lavelle and Spain 2001). There can be as many as 1000 earthworm and insect holes per m^2 of land. Earthworms and insects are particularly helpful in constructing large

holes in the soil that increase the percolation of water into the soil and decrease runoff.

Soil organic matter is an important source of nutrients and can help increase biodiversity, which provides vital ecological services, including crop protection (Pimentel et al. 2005). For example, adding compost and other organic matter reduces crop diseases (Cook 1988, Hoitink et al. 1991) and increases the number of species of microbes in the agroecosystem (van Elsen 2000). In addition, in the organic systems, not using synthetic pesticides and commercial fertilizers minimizes the harmful effects of these chemicals on nontarget organisms (Pimentel 2005).

In conventional crop management in New Zealand, Nguyen and Haynes (1995) did not report any adverse effect on soil microbial activity. These conventional systems, however, were part of a rotation pastoral–arable system with a relatively high level of soil organic matter (carbon content of the soil ranged from 2.9% to 3.5%).

Overall, environmental damage from agricultural chemicals was reduced in the organic systems because no commercial fertilizers or pesticides were applied to the organic systems. As a result, overall public health and ecological integrity could be improved through the adoption of these practices, which decrease the quantities of pesticides and commercial fertilizers applied in agriculture (BANR/NRC 2003, Pimentel 2005).

Oil and natural gas inputs. Significantly less fossil energy was expended to produce corn in the Rodale Institute's organic animal and organic legume systems than in the conventional production system (figure 1). There was little difference in energy input between the different treatments for producing soybeans. In the organic systems, synthetic fertilizers and pesticides were generally not used. Other investigators have reported similar findings (Karlen et al. 1995, Smolik et al. 1995, Dalgaard et al. 2001, Mader et al. 2002, Core 4 2003, Pimentel et al. 2005). In general, the use of less fossil energy by organic agricultural systems reduces the amount of carbon dioxide released to the atmosphere, and therefore the problem of global climate change (FAO 2003).

Crop yields and economics. Except for the 1999 drought year, the crop yields for corn and soybeans were similar in the organic animal, organic legume, and conventional farming systems. In contrast, Smolik and colleagues (1995) found that corn yields in South Dakota were somewhat higher in the conventional system, with an average yield of 5708 kg per ha, compared with an average of 4767 kg per ha for the organic legume system. However, the soybean yields in both systems were similar at 1814 kg per ha. In a second study comparing wheat and soybean yields, the wheat yields were fairly similar, averaging 2600 kg per ha in the conventional system and 2822 kg per ha in the organic legume system. Soybean yields were 1949 kg per ha and 2016 kg per ha for the conventional and the organic legume systems, respectively (Smolik et al. 1995). In the Rodale experiments, corn, soybeans, and wheat yields were considerably higher than those reported in South Dakota. These results might be expected, given the shorter growing season (146 days) and lower precipitation (460 mm) in South Dakota.

European field tests indicate that yields of organically grown wheat and other cereal grains average from 30% to 50% lower than conventional cereal grain production (Mader et al. 2002). The lower yields for the organic system in these experiments, compared with the conventional system, appear to be caused by lower nitrogen-nutrient inputs in the organic system. In New Zealand, wheat yields were reported to average 38% lower than those in the conventional system, a finding similar to the results in Europe (Nguyen and Haynes 1995). In New Jersey, organically produced sweet corn yields were reported to be 7% lower than in a conventional system (Brumfield et al. 2000). In the Rodale experiments, nitrogen levels in the organic systems have improved and have not limited the crop yields except for the first 3 years. In the short term, organic systems may create nitrogen shortages that reduce crop yields temporarily, but these can be eliminated by raising the soil nitrogen level through the use of animal manure or legume cropping systems, or both.

In a subsequent field test in South Dakota, corn yields in the conventional system and the organic alternative system were 7652 and 7276 kg per ha, respectively (Dobbs and Smolik 1996). Soybean yields were significantly higher in the conventional system, averaging 2486 kg per ha, compared with only 1919 kg per ha in the organic alternative system.

The Rodale crop yields were similar to the results in the conventional and organic legume farming system experiments conducted in Iowa (Delate et al. 2002). In the Iowa experiments, corn yields were 8655 and 8342 kg per ha for the conventional and organic legume systems, respectively. Soybean yields averaged 2890 kg per ha for the conventional farming system and 2957 kg per ha for the organic legume system.

Although the inputs for the organic legume and conventional farming systems were quite different, the overall economic net returns were similar without premiums (figure 2). Comparative net returns in the Rodale experiments differ from those of Dobbs and Smolik (1996), who reported a 38% higher gross income for the conventional than for the organic alternative system. However, Smolik and colleagues (1995) reported higher net returns for the organic alternative system in their study with alfalfa and nearly equal returns in the green manure treatment.

Prices for organic corn and soybeans in the marketplace often range from 20% to 140% higher than for conventional corn, soybeans, and other grains (Dobbs 1998, Bertramsen and Dobbs 2002, New Farm Organization 2003). Thus, when the market price differential was factored in, the differences between the organic alternative and conventional farming would be relatively small, and in most cases the returns on the organic produce would be higher, as in the results here for the FST.

In contrast to these results for corn and soybeans, the economic returns (dollar return per unit) for organic sweet corn production in New Jersey were slightly higher (2%) than for conventional sweet corn production (Brumfield et al. 2000). In the Netherlands, organic agricultural systems producing cereal grains, legumes, and sugar beets reported a net return of EUR 953 per ha, compared with conventional agricultural systems producing the same crops that reported EUR 902 per ha (Pacini et al. 2003).

In a California investigation of four crops (tomato, soybean, safflower, and corn) grown organically and conventionally, production costs for all four crops were 53% higher in the organic system than in the conventional system (Sean et al. 1999). However, the profits for the four crops were only 25% higher in the conventional system compared with the organic system. If the 44% price advantage of the four organically grown crops were included, the organic crops would be slightly more profitable than the conventional ones (Sean et al. 1999).

One of the longest-running organic agricultural trials (ongoing for more than 150 years) is the Broadbalk experiment at Rothamsted (formerly the Rothamsted Experimental Station) in the United Kingdom. The trials compared a manure-based organic farming system with a system based on synthetic chemical fertilizer. Wheat yields were slightly higher on average in the manured organic plots (3.45 t per ha) than in the plots receiving chemical fertilizers (3.40 t per ha). The soil quality improved more in the manured plots than in those receiving chemical fertilizer, based on greater accumulations of soil carbon (Vasilikiotis 2004).

Challenges for organic agriculture. Two primary problems with the organic system in the California study were nitrogen deficiency and weed competition (Sean et al. 1999). This was also noted for the organic faming systems in the US Midwest. Although the Rodale experiment overcame nitrogen deficiency challenges through legume cover crop management, other researchers have been less successful in maintaining and improving soil fertility levels in organic systems. Rodale's results could also be influenced by geographical soil characteristics and may not be universally applicable.

In organic production systems, pest control can be of heightened importance and impact. Weed control is frequently a problem in organic crops because the farmer is limited to mechanical and biological weed control, whereas under conventional production mechanical, biological, and chemical weed control options often are employed. Also, weather conditions can limit the efficacy of weed control. Mechanical weed control is usually more effective than chemical weed control under dry conditions, while the reverse holds true under wet conditions. In the Rodale experiments, only the organic soybeans suffered negative impacts from weed competition.

Insect pests and plant pathogens can be effectively controlled in corn and soybean production by employing crop rotations. Some insect pests can be effectively controlled by an increase in parasitoids; reports in organic tomato production indicate nearly twice as many parasitoids in the organic compared with the conventional system (Letourneau and Goldstein 2001). However, increased plant diversity in tomato production was found to increase the incidence of plant disease (Kotcon et al. 2001). With other crops, like potatoes and apples, dealing with pest insects and plant pathogens that adversely affect yields is a major problem in organic crop production.

Adoption of organic technologies. Several organic technologies, if adopted in current conventional production systems, would most likely be beneficial. These include (a) employing off-season cover crops; (b) using more extended crop rotations, which act both to conserve soil and water resources and also to reduce insect, disease, and weed problems; (c) increasing the level of soil organic matter, which helps conserve water resources and mitigates drought effects on crops; and (d) employing natural biodiversity to reduce or eliminate the use of nitrogen fertilizers, herbicides, insecticides, and fungicides. Some or all of these technologies have the potential to increase the ecological, energetic, and economic sustainability of all agricultural cropping systems, not only organic systems.

Conclusions

Various organic agricultural technologies have been used for about 6000 years to make agriculture sustainable while conserving soil, water, energy, and biological resources. The following are some of the benefits of organic technologies identified in this investigation:

- Soil organic matter (soil carbon) and nitrogen were higher in the organic farming systems, providing many benefits to the overall sustainability of organic agriculture.
- Although higher soil organic matter and nitrogen levels were identified for the organic systems, similar rates of nitrate leaching were found to those in conventional corn and soybean production.
- The high levels of soil organic matter helped conserve soil and water resources and proved beneficial during drought years.
- Fossil energy inputs for organic crop production were about 30% lower than for conventionally produced corn.
- Depending on the crop, soil, and weather conditions, organically managed crop yields on a per-ha basis can equal those from conventional agriculture, although it is likely that organic cash crops cannot be grown as frequently over time because of the dependence on cultural practices to supply nutrients and control pests.
- Although labor inputs average about 15% higher in organic farming systems (ranging from 7% to 75% higher), they are more evenly distributed over the

year in organic farming systems than in conventional production systems.

- Because organic foods frequently bring higher prices in the marketplace, the net economic return per ha is often equal to or higher than that of conventionally produced crops.
- Crop rotations and cover cropping typical of organic agriculture reduce soil erosion, pest problems, and pesticide use.
- The recycling of livestock wastes reduces pollution while benefiting organic agriculture.
- Abundant biomass both above and below the ground (soil organic matter) also increases biodiversity, which helps in the biological control of pests and increases crop pollination by insects.
- Traditional organic farming technologies may be adopted in conventional agriculture to make it more sustainable and ecologically sound.

Acknowledgments

We thank the following people for reading a draft of this article and for their many helpful suggestions: Robin G. Brumfield, Rutgers, The State University of New Jersey; Wen Dazhong, Institute of Applied Ecology, Academia Sinica, Shenyang, China; Tomek De Ponti, Visiting Fulbright Scholar, Cornell University; Andrew R. B. Ferguson, Optimum Population Trust, Oxon, United Kingdom; Long Nguyen, National Institute of Water and Atmospheric Research, Auckland, New Zealand; Maurizio Paoletti, Università di Padova, Italy; James Smolik, South Dakota State University; Chris Wien, Cornell University.

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