Long-Term Agronomic Performance of Organic and Conventional Field Crops in the Mid-Atlantic Region

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ABSTRACT

Despite increasing interest in organic grain crop production, there is inadequate information regarding the performance of organically-produced grain crops in the United States, especially in Coastal Plain soils of the mid-Atlantic region. We report on corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) yields at the USDA-ARS Beltsville Farming Systems Project (FSP), a long-term cropping systems trial established in Maryland in 1996 to evaluate the sustainability of organic and conventional grain crop production. The five FSP cropping systems include a conventional no-till corn–soybean–wheat/soybean rotation (NT), a conventional chisel-till corn–soybean–wheat/soybean rotation (CT), a 2-yr organic corn–soybean rotation (Org2), a 3-yr organic corn–soybean–wheat rotation (Org3), and a 4- to 6-yr organic corn–soybean–wheat–hay rotation (Org4+). Average corn grain yield during 9 yr was similar in NT and CT (7.88 and 8.03 Mg ha^{-1}, respectively) but yields in Org2, Org3, and Org4+ were, respectively, 41, 31, and 24% less than in CT. Low N availability explained, on average, 73% of yield losses in organic systems relative to CT while weed competition and plant population explained, on average, 23 and 4%, respectively, of these yield losses. The positive relationship between crop rotation length and corn yield among organic systems was related to increasing N availability and decreasing weed abundance with increasing rotation length. Soybean yield averaged 19% lower in the three organic systems (2.88 Mg ha^{-1}) than in the conventional systems (3.57 Mg ha^{-1}) and weed competition alone accounted for this difference. There were no consistent differences in wheat yield among cropping systems. Crop rotation length and complexity had little impact on soybean and wheat yields among organic systems. Results indicate that supplying adequate N for corn and controlling weeds in both corn and soybean are the biggest challenges to achieving equivalent yields between organic and conventional cropping systems.

The number of acres under organic management worldwide has increased rapidly in recent years (Yussefi, 2006). In the United States the number of certified organic crop acres increased by 24% per year, on average, between 1992 and 2003, making the organic sector one of the fastest growing segments of agriculture for at least 10 yr (Greene, 2006). Meat and milk are the fastest growing sectors of the organic industry (Dimitri and Greene, 2002; USDA-ERS, 2006b) and this growth has resulted in price premiums for organic grains (corn, soybean, wheat) that, from 2000 to 2005, were two to three times greater than those for conventionally-grown grains (Streff and Dobbs, 2004; M. Hamilton, North Carolina State Univ., personal communication, 2006; USDA-ERS, 2006a).

In the mid-Atlantic region, organic price premiums have recently attracted the interest of conventional grain farmers, and grain brokers are helping to facilitate more adoption of local organic grain production (L. Howard, Mid-Atlantic Brokerage, personal communication, 2006). Concomitantly, the Natural Resources Conservation Service (NRCS) is supporting organic farming in some states due to the potential resource conservation benefits of organic production (Green et al., 2005; Pimentel et al., 2005; Marriott and Wander, 2006; USDA-NRCS, 2006). In 2006, NRCS-Maryland spent more than $500,000 in its Transitioning to Organic Production program with more than half the funds used to support grain farmers who also meet EQIP guidelines. The NRCS-Maryland support for organic farming is expected to continue (E. Dengler, NRCS, personal communication, 2006).

Despite increasing interest in organic grain crop production, adequate information on expected crop yields and production challenges is lacking for many areas of the United States, especially in the mid-Atlantic region. To our knowledge, there have been no published papers on organic grain production in the Coastal Plain soils region of the mid-Atlantic region, an area that includes portions of all states between New Jersey and North Carolina and where 29% of land is used for agriculture (Atorand et al., 2000). Grain yields of crops grown under organic conditions in other regions of the United States have been reported to be similar or lower than yields in conventional systems (Lockeretz et al., 1981; Drinkwater et al., 1998; Welsh, 1999; Robertson et al., 2000; Poudel et al., 2002; Porter et al., 2003; Delate and Cambardella, 2004). However, only a few studies have measured the impact of crop rotation length and complexity on crop performance in organic systems (Porter et al., 2003).

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Abbreviations: CT, chisel tillage; FSP, Farming Systems Project; NT, no-tillage; Org2, 2-year organic crop rotation; Org3, 3-year organic crop rotation; Org4+, 4- to 6-year organic crop rotation.

Among conventional systems, there is evidence that longer, more complex rotations can provide several benefits compared to shorter, simpler rotations, including higher crop—especially corn—yields (Clay and Aguilar, 1998; Singer and Cox, 1998; Katsvairo and Cox, 2000; Meyer-Aurich et al., 2006), increased soil quality (Karlen et al., 2006), decreased weed pressure (Clay and Aguilar, 1998), and greater profits (Singer et al., 2003; Meyer-Aurich et al., 2006), although benefits are not consistently realized (Porter et al., 2003; Singer et al., 2003). For organic systems, there is evidence that increased rotation length and complexity can reduce weed populations (Teasdale et al., 2004b) but the impact of these weeds on crop yields is not well characterized. It is not known whether the restricted use of herbicides and N fertilizers in organic production systems (USDA-AMS, 2006) limits the applicability of findings from conventional systems to organic production systems.

Surveys of organic farmers indicate that weed control is the biggest challenge in organic grain production (Walz, 1999). Despite the certainty that crop yield loss will increase with increasing weed abundance (Kropff and van Laar, 1993; Canner et al., 2002), the degree of yield loss can vary depending on many factors. When soil moisture is limiting, crop yield loss is often higher than under adequate moisture conditions (Toler et al., 1996; Cowan et al., 1998). Likewise, deficient N conditions can enhance corn yield loss from competition with weeds (Tollenaar et al., 1994; Cathcart and Swanton, 2003; Evans et al., 2003). However, cropping systems that rely on organic soil amendments and cover crops for fertility can reduce the competitiveness of weeds compared to conventional systems that rely on synthetic fertilizer inputs (Dyck et al., 1995; Williams et al., 1998; Liebman and Davis, 2000; Davis and Liebman, 2001).

Surveys of organic farmers indicate that, after weed control, soil fertility is the biggest challenge in organic grain production (Walz, 1999). Organic farmers generally rely on leguminous green manure cover crops and/or animal manures to supply crops with N. Nitrogen contributions of organic sources are notoriously variable: N contributions of legume green manure crops, for example, range from 0 to 159 kg N ha^{-1} (Oyer and Touchton, 1990; Hesterman et al., 1992; Reinbott et al., 2004). The amount of N in green manure crops is influenced by growing conditions including green manure planting and kill dates, soil moisture, and growing degree days (Clark et al., 1994, 1997; Sainju and Singh, 2001; Teasdale et al., 2004a). Among the factors influencing the amount of organic and ammonium N in animal manures are livestock species, diet, storage, and handling methods (Bussink and Oenema, 1998; Meisinger and Jokela, 2000). For both green and animal manures, even when organic and ammonium N contents are known, N availability is variable because of the impacts of soil moisture and temperature (Ruffo and Bollero, 2003a), plant tissue and manure chemical composition other than N (Gordillo and Cabrera, 1997; Heal et al., 1997; Ruffo and Bollero, 2003b), and tillage (Sainju and Singh, 2001) on N mineralization. In addition, N volatilization rates from organic sources, especially when not immediately incorporated into soil, show wide variability (Bussink and Oenema, 1998; Meisinger and Jokela, 2000). There is a need to understand the impact of organic sources of N on crop yields in a time frame that considers the broad range of variability regularly experienced by farmers. Also, more information is needed on the relative importance of weed competition and N availability on crop yield potential in organic cropping systems. Long-term experiments can provide these types of data.

In this paper, we report on 10 yr of crop yield data from a long-term cropping systems study in Maryland, the USDA-ARS Beltsville FSP, which was established to evaluate the sustainability of organic and conventional cropping systems. We determined the impacts of weed competition and N inputs on yield variability in organic and conventional systems.

MATERIALS AND METHODS

Study Site

The study site is 16 ha in size and is at the western edge of the Atlantic Coastal Plain at the USDA-ARS Beltsville Agricultural Research Center in Beltsville, MD. The dominant soil types are Christiana (fine, kaolinitic, mesic Typic Paleudults), Matapeake (fine-silty, mixed, semiactive, mesic Typic Hapludults), Keyport (fine, mixed, semiactive, mesic Aquic Hapludults), and Mattapex (fine-silty, mixed, active, mesic Aquic Hapludults) silt loams. The site had not been tilled for 11 yr before plot establishment in 1996. The 30-yr average annual precipitation at the site is 1110 mm, distributed evenly through the year. Average annual temperature is 12.8°C.

Table 1. Summary of typical cropping systems management at the USDA-ARS Beltsville Farming Systems Project.

Management practice	Cropping systems				
	No till	Chisel till	Organic 2-yr	Organic 3-yr	Organic 4+-yr
Crop rotation†	C-r-S-W/S	C-r-S-W/S	C-r-S-v	C-r-S-W-v	C-r-S-W-H
Primary tillage‡	None	Ch	D, MB, or Ch	D, MB, or Ch	D, MB, or Ch
Weed control§	Herbicides	Herbicides	RH, RC	RH, RC	RH, RC
Fertility¶	N, P, K	N, P, K	GM, AM, K_2SO_4	GM, AM, K_2SO_4	GM, AM, K_2SO_4

† C = corn; S = soybean; W = wheat; W/S = wheat followed by double-cropped soybean; H = hay, 1 yr of red clover + orchardgrass (1996–2001) or 3 yr of alfalfa (2000–2005); r = rye cover crop; v = hairy vetch or hairy vetch mix green manure cover crop. No till and chisel till followed a 2-yr C-W/S rotation from 1996 to 2000.

‡ D = disk, MB = moldboard plow, Ch = chisel plow. For organic systems, disk was used for all crops, 1996 to 1998, and for wheat, 1996 to 2005; moldboard plow was used for corn in Org2 and Org3, 2003 to 2005, and in Org4+, 1999 to 2005; chisel plow was used for soybean in Org2, Org3, and Org4+, 2003 to 2005. There was no primary tillage for corn in Org2 and Org3 and for soybean in all three organic systems from 1999 to 2002.

§ RH = rotary hoe, RC = row cultivator. Rotary hoe was not used 1999 to 2002 in Org2 and Org3.

¶ N = ammonium nitrate or urea ammonium nitrate, P = triple super phosphate, K = potassium chloride, GM = green manures, AM = animal manures, K_2SO_4 = potassium sulfate

Cropping Systems and Cultural Practices

The FSP includes two conventional and three organic cropping systems (Table 1). The three organic cropping systems (Org2, Org3, and Org4+) differ in crop rotation length and complexity. In all five systems, a rye (*Secale cereale* L.) cover crop was planted after corn. Hairy vetch (*Vicia villosa* Roth) was planted in late summer or fall to serve as a green manure for corn in Org2 and Org3. Commercial-scale farm equipment is used for all field management operations.

Each phase of each crop rotation is represented every year. Cropping systems are replicated four times in a split-plot design with system assigned to whole plots and crop rotation phase assigned to subplots, which represent the experimental units and which we refer to as plots in this paper. Each of the 68 total plots (17 rotation phase plots replicated four times) is 9.1 m wide and 111 m long (0.1 ha in size).

Corn

Corn was planted in early May in the conventional systems. In the organic systems corn was planted in late May to maximize green manure crop biomass and N content, and to allow weeds to germinate before final seedbed preparation. In all five systems, corn was planted in rows spaced 76 cm apart at an average seeding rate of 67,600 seeds ha^{-1}. The conventional systems received, on average, 160, 12, and 45 kg ha^{-1} N, P, and K each year. About 30% of fertilizer N was broadcast before planting as ammonium nitrate, about 10% was in the starter fertilizer blend, and about 60% was sidedressed as urea ammonium nitrate when the corn was at about the V5 development stage. The herbicide program in the NT system included 0.56 kg a.i. ha^{-1} 2,4-D (2,4-dichlorphenoxyacetic acid), 0.52 kg a.i. ha^{-1} paraquat (1,1'-dimethyl-4,4'-bipyridinium ion), 1.90 kg a.i. ha^{-1} metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide], and 1.94 kg a.i. ha^{-1} atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine). Metolachlor (1.74 kg a.i. ha^{-1}) and atrazine (1.78 kg a.i. ha^{-1}) were used in the CT system. Beginning in 2004 simazine (6-chloro- *N*, *N*'-diethyl-1,3,5-triazine-2,4-diamine) was added to the pre-emergence herbicide program in both NT (1.78 kg a.i. ha^{-1}) and CT (1.22 kg a.i. ha^{-1}) systems to address late season grass emergence. Metolachlor and atrazine concentrations were concomitantly reduced to 1.33 and 0.34 kg a.i. ha^{-1}, respectively. In 1996 and 1997 (NT only) and 2004 and 2005 (NT and CT) 0.11 kg a.i. ha^{-1} permethrin (3-phenoxyphenyl)methyl *cis*,trans-(+-)-3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate) was used for cutworm (Family Noctuidae) control.

In the organic systems a legume green manure crop, which was planted using a grain drill in early September in Org3 and in October in Org2, was the primary source of N. In Org4+ the perennial hay crop served as a green manure crop. In years when the legume portion of the green manure crop stand was considered too thin to provide adequate N for corn, animal manure, or animal manure compost was applied before planting corn. This option was used conservatively because of high to excessive soil P at this site. The Org2 received 5420 kg ha^{-1} broiler litter compost in 1998, and 6720 kg ha^{-1} broiler or layer litter from 2003 to 2005. The Org3 received 11,740 kg ha^{-1} broiler litter compost in 1998 and 4480 kg ha^{-1} broiler or layer litter in 2003 and 2004. The Org4+ received 5600 kg ha^{-1} broiler litter in 1998 and 2000, 124,000 L ha^{-1} dairy manure slurry in 2002, and 6720 kg ha^{-1} layer litter in 2004 and 2005.

Tillage in the CT system included one pass with a chisel plow, and one to two passes with a disk. In the organic systems, from 1996 to 1998, primary tillage involved two to three passes with a disk and/or field cultivator. A rotary hoe was typically used twice, about 5 and about 10 d after planting, and a row cultivator was typically used twice, about 3 wk and about 4 wk after planting to control weeds. From 1999 to 2005, the hay crop in Org4+ was killed using a moldboard plow followed by one to three passes of a disk. A rotary hoe and a row cultivator were used two times each as described above. From 1999 to 2002 a reduced tillage system was used in Org2 and Org3 (Teasdale and Rosecrance, 2003). Instead of primary tillage, the hairy vetch cover crop was crushed using a corn stalk chopper after flowering and left on the soil surface as a mulch; corn was then planted using a no-till planter, and a high residue cultivator was used two to three times for weed control. Due to poor weed control and a heavy infestation of ryegrass in 2002, the more traditional organic management protocol was used from 2003 to 2005, which was essentially the same as that used in Org4+ from 1999 to 2005.

Full-Season Soybean

Soybeans were planted in early to late May in the conventional systems and in late May in the organic systems at an average seeding rate of 526,400 seeds ha^{-1}. Roundup-Ready soybean cultivars were planted in the conventional systems in 19 cm rows; non-Roundup-Ready cultivars were planted in the organic systems in 76 cm rows. The soybean in the conventional systems received, on average, 4 and 66 kg ha^{-1} P and K, respectively, a preplant application of 0.63 kg a.i. ha^{-1} paraquat, and a postemergence application of 1.68 kg a.i. ha^{-1} glyphosate (*N*-(phosphonomethyl)glycine) each year. The Org2, Org3, and Org4+ received, on average, 24, 27, and 42 kg ha^{-1} K as K_2SO_4, respectively, per year. The Org2 and Org3 received 5725 kg ha^{-1} composted broiler litter in 1998.

Tillage in the CT system included one pass each with a chisel plow, a disk, and a field cultivator. Tillage in the organic systems was similar to that used for organic corn. From 1996 to 1998, two passes with a disk served as primary tillage, and two passes each with a rotary hoe and a row cultivator were used for weed control after planting. From 1999 to 2002 a reduced tillage system was used in all three organic systems, in which the rye cover crop was killed by flail mowing after flowering, soybeans were planted using a no-till planter, and a high residue cultivator was used for weed control. From 2003 to 2005, rye was killed using a chisel plow followed by disking and weed control after planting was achieved using a rotary hoe and row cultivator as described for corn.

Double-Cropped Soybean

Roundup-Ready soybean was planted at 527,000 seeds ha^{-1} using a no-till drill in early July following wheat harvest in the conventional systems. Glyphosate (1.68 kg a.i. ha^{-1}) was applied for weed control just before soybean formed a full canopy.

Winter Wheat

Winter wheat was planted at about 160 kg seed ha^{-1} in mid- to late October in the NT, CT, Org3, and Org4+ systems. Conventional systems received, on average, 28 kg N ha^{-1} at planting and 80 kg N ha^{-1} topdressed in early spring as 30% UAN. Weeds were controlled using 18 g a.i. ha^{-1} thifensulfuron (3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] amino]sulfonyl]-2-thiophenecarboxylic acid) and 9 g a.i. ha^{-1} tribenuron (2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) methylamino] carbonyl]amino]sulfonyl]benzoic acid), which were applied with the spring fertilizer. Poultry litter (6300 kg ha^{-1}) was applied to wheat as topdressing (through spring 2000) or incorporated into the soil at planting (fall 2000 and later) in the organic systems. Since the experiment was started in spring 1996, there was no wheat harvest that year.

Cover Crops and Hay Crops

Corn stalks were mowed after harvest and rye (125 kg seed ha^{-1}) was planted using a no-till drill in the conventional systems from 2000 to 2005 and in the organic systems from 1996 to 2005. The hairy vetch cover crop was planted after soybean harvest in Org2 and in late August or early September after wheat in Org 3 at 45 kg seed ha^{-1}. In the fall of 1996 and 1997 the cover crop in both Org2 and Org3 was a mix of crimson clover (*Trifolium incarnatum* L.) (17 kg seed ha^{-1}), hairy vetch (25 kg seed ha^{-1}), and rye (35 kg seed ha^{-1}). In Org4+, the hay crop before 2000 was a red clover (*T. pratense* L.) plus orchardgrass (*Dactylis glomerata* L.) mix sown at 17 and 18 kg seed ha^{-1}, respectively, in the fall. Alfalfa (*Medicago sativa* L.), which was first planted in 2000, was seeded in late August at 17 kg seed ha^{-1}.

Management Changes

In 2000, three of the cropping systems were adjusted to address specific production issues identified by our project focus group, which was composed of farmers and agricultural professionals. From 1996 to 2000 the crop rotation in the two conventional systems was a 2-yr corn–wheat/double-crop soybean rotation. The rotation was expanded to the current 3-yr rotation in 2001 by including a full-season soybean crop after the corn to address concerns about plant diseases in wheat following corn in the NT system. The CT system had employed reduced inputs before 2000 but was converted to a system with conventional inputs in 2000. Results from the initial reduced input phase of CT are not reported in this paper. Beginning in 2000, alfalfa instead of red clover plus orchardgrass was planted as the hay crop in Org4+. When alfalfa—which provides a N credit two to three times greater than that for red clover (Mullins and Hansen, 2006)—was incorporated into the crop rotation, the duration of the hay crop was lengthened from 1 to 3 yr resulting in expansion of the rotation length from 4 to 6 yr. The designation Org4+ is used to indicate a rotation length of 4 or more years.

Other management changes were dictated by weather conditions. For example, from 2002 to 2005, no green manure crop was planted in Org2 because wet soil conditions after soybean harvest precluded planting hairy vetch. For the same reason, wheat was not planted in any system in fall 2002 and 2003 and in the organic systems in fall 2004. In years when winter wheat was not planted in conventional systems, full season soybeans were planted the following spring using the protocol described above. In organic systems, a sudangrass silage crop was planted the spring of the following year. The sudangrass was harvested in August to allow adequate time for planting the hairy vetch or alfalfa crop in Org3 and Org4+, respectively.

In spite of changes in crop rotation and some management practices, the fundamental differences among the five systems remained distinct from each other for the duration of the experiment; that is, NT and CT were managed using practices common in the region and the three organic systems differed in crop rotation length and complexity while relying on cultivation for weed control and on organic sources for N inputs.

Soil Sampling and Analyses

Soil samples were taken in the fall and results of analyses were used to guide soil fertility programs according to University of Maryland recommendations. Eight to 12 soil cores per plot were combined to form one sample, which was air-dried and sent to the University of Maryland soil testing lab (College Park, MD; operations discontinued in 2003) or to A&L Great Lakes Laboratories (Fort Wayne, IN). Soils were amended with lime when soil pH fell to 6.7 for legume forage crops and 6.2 for all other crops as recommended by the University of Maryland.

Crop and Green Manure Yields and Nutrient Contents

Crop yields were measured by transferring the combine contents after harvesting the middle 3 m of plots into a weigh wagon, measuring grain moisture with a moisture meter and adjusting corn grain yields to 0.155 and soybean and wheat yields to 0.135 g kg^{-1} water content. In 2002, corn and soybean in the three organic cropping systems were harvested and threshed by hand due to a very heavy weed infestation and low yields caused by drought.

To ensure representative plant and soil sampling, plots were divided into four equal length quadrants (approximately 28 m in length, 9.1 m wide). Green manure crop biomass estimates were made by cutting all aboveground plant material within one 0.25 m^2 quadrat per quadrant. Plant material from all quadrants within a plot was combined to give one sample per plot. Corn ear leaves were sampled at silking from 20 to 30 plants per plot as a measure of relative N uptake (Jones et al., 1990) in 1996, 1997, and 2000 to 2002. Plant material was oven-dried to constant weight at 65°C, weighed, ground to pass a 1-mm sieve and sent to A&L Great Lakes Laboratories, where total N was determined. Total N content of legume green manure crops was calculated by multiplying biomass values by tissue N concentrations. Availability of green manure crop N to succeeding crops was estimated by assuming that 50% of aboveground green manure crop N was available to the succeeding corn crop (Sarrantonio, 1994). For perennial green manure crops, underground N contributions were added to these measurements based on legume crop nitrogen credits developed at the University of Maryland (Mullins and Hansen, 2006).

Animal Manure and Compost Analyses

Animal manures and composts were sampled soon before application and sent to the University of Maryland soil testing lab or to A&L Great Lakes Laboratories, where they were analyzed for total and ammonium (NH_4) N. Nitrogen availability from animal manures and composts for the first year after application was determined according to the equation:

$$\text{N availability} = (\text{Total N} - NH_4 - N) \times a + (NH_4 - N) \times b,$$

where *a*, the percent organic N mineralized, is 0.50 for poultry litter, 0.35 for dairy manure, and 0.15 for composts; and *b*, the NH_4–N volatilization coefficient, is 1, 0.8, 0.64, 0.48, 0.32, 0.16, or 0 when there is, respectively, 0, 1, 2, 3, 4, 5 or 6+ days between the time the sample is taken and the time the manure or compost is incorporated into the soil. The zero day value is used only when manure is injected; the 1 d value is used when manure is surface applied and incorporated on the same day (Paul Shipley, University of Maryland, personal communication, 2006).

Weed Abundance

The length of each plot was divided into four 28 m-long quadrants, excluding areas at the plot ends. The percentage of soil area covered by weeds was estimated visually within the middle six rows of each quadrant of each corn and soybean plot at weed maturity in early September. Cover estimates were subdivided by major species but annual grasses were estimated as a single group.

Statistical Analyses

Analyses of variance for crop yield, weed cover, green manure crop biomass and N content, corn ear leaf N, estimated available N inputs, and crop population were conducted by year and crop with cropping system as a fixed effect and block as random effect using PROC MIXED (SAS Version 9.1, SAS Inst., Cary, NC). Analyses across years were conducted as above except with block and year as random effects. Variance partitioning was employed only when the AIC statistic output by PROC MIXED was lower with variance grouping than without it.

A covariance analysis was performed to assess the influence of weed cover, N inputs, and population on crop yield. Preliminary analyses showed that crop yield varied considerably across the years of this trial because of a wide range of optimal to suboptimal weather conditions. There was generally an insufficient range of yield values in the suboptimal years to identify significant relationships. Thus, analyses were only performed on data from 5 yr when relatively good rainfall prevailed and yields were relatively high (1996, 2000, 2001, 2004, and 2005). The analysis was conducted using PROC MIXED in three steps. First, the regression of corn yield on weed cover, N input, or corn population was conducted separately with block and year treated as random class effects. Second, each of these variables was entered into a multiple regression model in order of ascending AIC statistic determined in the previous step and kept in the final model if the coefficient was significant ($P < 0.05$). Third, system was added to the resulting multiple regression model as a class variable to determine if the regression accounted for system effects. Soybean yield was only regressed as a function of weed cover.

RESULTS AND DISCUSSION

Grain Yield

Corn and soybean grain yields varied considerably by year and by cropping system (Table 2). Yearly variation in crop yield was due in large part to differences in precipitation. For example, corn and soybean yields were very low from 1997 to 1999 and in 2002 when precipitation from May to August was about 60% of the 30-yr average (Table 3). Precipitation was so low in 1999 that no crops were harvested for grain. Low corn yields in 2003 were due to high rainfall in the spring, which limited weed control operations and decreased soil N availability as discussed in more detail below.

There were no differences in corn grain yield between NT and CT except in 2003 (Table 2). Average corn grain yields for the years 2000 to 2005, the period when all five systems were represented, were similar in the two conventional systems while yields in Org2, Org3, and Org4+ were lower than that in CT by 41, 31, and 24%, respectively. The positive relationship between crop rotation length and corn grain yield and greater corn yield following a perennial legume than following summer annual crops among organic systems is consistent

Table 2. Corn, full-season soybean, and wheat yields harvested from the Farming Systems Project, Beltsville, MD. The Org2, Org3, and Org4+ are, respectively, 2-, 3-, and 4- to 6-yr organic crop rotations.

		Grain yield									
Crop	System	1996	1997	1998	2000	2001	2002	2003	2004	2005	Mean†
		Mg ha^{-1}									
Corn	No till	9.79 a‡	3.83 a	1.81 a	8.20 ab	7.75 a	3.81 a	4.30 b	12.5 a	10.3 ab	7.81 a
	Chisel till§	–	–	–	9.09 a	7.81 a	3.36 a	5.59 a	11.7 a	10.6 a	8.03 a
	Org2	7.70 b	1.67 b	1.92 a	7.56 b	4.89 b	0.08 c	2.38 c	7.38 b	6.09 d	4.73 d
	Org3§	–	2.79 ab	2.31 a	7.81 b	4.82 b	0.55 b	3.16 c	8.08 b	8.89 c	5.55 c
	Org4+§	–	–	2.72 a	8.12 b	7.95 a	0.98 b	2.71 c	8.33 b	8.72 bc	6.13 b
Soybean	No till	–	–	–	–	4.31 a	1.75 a	4.05 a	4.03 a	4.35 a	3.70 a
	Chisel till§	–	–	–	–	4.24 a	2.05 a	3.39 b	3.63 a	4.16 ab	3.49 a
	Org2	4.53	2.61	2.30 a	4.76 a	3.58 ab	0.68 c	2.38 c	3.54 a	3.72 bc	2.78 b
	Org3§	–	–	1.94 a	4.91 a	3.28 b	0.87 c	2.98 b	3.74 a	3.37 c	2.85 b
	Org4+§	–	–	–	4.78 a	3.09 b	1.27 b	2.95 b	3.66 a	4.04 ab	3.00 b
Wheat	No till	–	5.27 a	3.89 a	3.29 a	4.63 b	4.03 c	–	–	5.04 a	3.98 a
	Chisel till§	–	–	–	2.97 a	4.79 b	5.01 ab	–	–	5.00 a	4.26 a
	Org3	–	4.50 a	4.21 a	1.61 b	5.24 a	4.78 b	–	–	–	3.88 a
	Org4+	–	–	4.22 a	1.77 b	5.50 a	5.45 a	–	–	–	4.24 a

† Means are for years when all five cropping systems were represented: for corn, 2000 to 2005; for soybean, 2001 to 2005; for wheat, 2000 to 2002.

‡ Values within crop and year followed by the same letter are not significantly different at $P < 0.05$.

§ Values in 1996 to 1998 are omitted for Chisel till, which was managed with reduced inputs, and for Org3 and Org4+ when the rotation was not fully established.

Table 3. Average monthly precipitation, May to August, 1996 to 2005, and 30-yr mean, Beltsville, MD.

Month	Average monthly precipitation										
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	30-yr mean
	mm										
May	114	57	95	41	63	105	70	160	73	78	115
June	163	82	84	48	118	144	56	165	86	73	91
July	106	34	38	19	144	149	61	164	171	172	104
August	70	70	31	127	86	112	64	76	77	91	94
Mean	113	61	62	59	103	128	63	141	102	104	101

with findings from studies in conventional systems (Clay and Aguilar, 1998; Singer and Cox, 1998; Singer et al., 2003; Meyer-Aurich et al., 2006).

There were no differences in full-season soybean yield between NT and CT except in 2003 (Table 2). Full-season soybean yields in the conventional systems tended to be numerically higher than yields in the organic systems but differences were not always significant. When averaged over 2001 to 2005, the years that full-season soybeans were present in all systems, soybean yield was higher ($P < 0.05$) in the two conventional systems (3.57 Mg ha^{-1}) than in the three organic systems (2.88 Mg ha^{-1}). Double-crop soybeans were grown in conventional systems in all years but there were no differences between NT and CT double-crop soybean yield in any year (data not shown) or in average double-crop soybean yield across years (1.96 and 1.93 Mg ha^{-1}, respectively). There were no consistent differences in wheat yields among systems within years and there were no differences in average wheat yield from 2000 to 2002 (Table 2), the only years when all four cropping systems included wheat.

Weed Cover

Weed cover in corn was greater in Org2 than in the conventional systems in 7 of 9 yr and was greater than in the longer organic rotations in 5 of 8 yr (Table 4). Likewise, weed cover in full-season soybean was higher in Org2 than in conventional systems in every year and was higher than in the other organic systems in 4 of 7 yr. Weed cover was lower in Org4+ than in the two shorter organic rotations in 3 of 7 yr in corn and 5 of 6 yr in soybean. The reduction of weed abundance and seedbank populations by longer, more diverse rotations of the FSP organic cropping systems has been described in detail by Teasdale et al. (2004b). Generally, the greater number and diversity of operations resulting in weed mortality in the Org4+ rotation accounted for lower populations of the dominant summer annual weeds, smooth pigweed (*Amaranthus hybridus* L.) and common lambsquarters (*Chenopodium album* L.), in this system. Weather-related interference with timely weed control operations caused deviations from this generalization in some years. For example, weed control was poor in Org4+ in 2000 and 2003 corn because high rainfall in late spring prevented timely cultivations and in 2002 because dry weather prevented development of a competitive corn crop (Table 4). Unfavorable weather patterns also accounted for weed control failures in the conventional systems, namely, in NT corn in 2001 and in both NT and CT corn in 2003 when heavy rain facilitated dissipation of residual herbicides and prevented application of postemergence herbicides.

Table 4. Soil area covered by weeds at weed maturity in corn and full-season soybean. The Org2, Org3, and Org4+ are, respectively, 2-, 3-, and 4- to 6-yr organic crop rotations.

Crop	System	Weed cover								
		1996	1997	1998	2000	2001	2002	2003	2004	2005
		%								
Corn	No till	10 a†	16 b	15 c	21 c	50 b	3 d	73 a	5 c	0.5 c
	Chisel till‡	–	–	–	23 c	8 d	8 c	31 c	2 d	0.2 c
	Org2	8 a	50 a	65 a	71 a	68 a	84 a	54 b	35 a	36.6 a
	Org3‡	–	23 b	29 b	63 b	53 b	21§ b	49 b	14 b	9.9 b
	Org4+‡	–	–	32 b	74 a	28 c	75 a	56 b	3 d	2.5 c
Soybean	No till	–	–	–	–	2 c	5 d	5 d	0.0 c	0.1 d
	Chisel till‡	–	–	–	–	1 d	1 d	13 c	0.2 c	0.6 c
	Org2	18	35	48 a	24 a	46 b	65 a	49 a	9.4 a	34.6 a
	Org3‡	–	–	12 b	13 b	45 b	32 b	32 b	16.5 a	49.3 a
	Org4+‡	–	–	–	7 c	65 a	23 c	19 c	1.0 b	16.1 b

† Values within crop and year followed by the same letter are not significantly different at $P < 0.05$.

‡ Values between 1996 and 1998 are omitted for Chisel till, which was managed with reduced inputs, and for Org3 and Org4+ when the rotation was not fully established.

§ This value does not include a substantial infestation of annual ryegrass in spring that had senesced by the time these ratings were conducted.

Nitrogen Availability

Estimated N availability among organic systems varied by green manure type (Table 5). Vetch, mixed hay, and alfalfa provided an estimated 38 to 81 (mean = 68), 17 to 33 (mean = 25), and 45 to 109 (mean = 76) kg available N ha^{-1}, respectively. Nitrogen availability from vetch is consistent with that reported by Decker et al. (1994) and Reinbott et al. (2004) while alfalfa N availability is less than or consistent with that presented by Bruulsema and Christie (1987). Even though vetch in Org3 was planted about 2 mo earlier than vetch in Org2, vetch biomass and N content were greater in Org3 than in Org2 in only 1 of 4 yr. However, vetch was not planted in Org2 in 3 of 10 yr because soils were too wet to harvest soybean or to plant vetch in October, while vetch was planted in Org3 all 10 yr of the study. Thus, vetch was a more reliable, although not always a more productive, source of N when planted in September in Org3 than when planted in October in Org2. Alfalfa provided more N than that provided by vetch in 2001 only (Table 5). However, we cannot generalize about N inputs from alfalfa vs. vetch since alfalfa served as the green manure crop in only 3 yr. In addition, alfalfa had been planted the previous fall in two of these years, once as part of the transition to the alfalfa-based hay rotation (2001), and once

Table 5. Green manure biomass and N content, estimated available N inputs, and source of N inputs for corn. The Org2, Org3, and Org4+ are, respectively, 2-, 3-, and 4- to 6-yr organic crop rotations.

System	1996	1997	2000	2001	2002	2003	2004	2005
Green manure biomass, Mg ha^{-1}								
Org2	4.13	5.30 b†	4.48 a	2.59 b	3.30 a	–	–	–
Org3‡	–	7.65 a	4.51 a	3.74 b	3.82 a	–	3.58	4.16 a
Org4+‡	–	–	2.24 b	5.86 a	2.42 b	2.28	–	2.72 b
Green manure N content, kg ha^{-1}								
Org2	143	112 b	160 a	76 b	137 a	–	–	–
Org3‡	–	162 a	160 a	120 b	141 a	–	126	146 a
Org4+‡	–	–	35 b	218 a	66 b	148	–	89 b
Estimated available N inputs,kg ha^{-1}§								
No till	192 a	159 a	174 a	120 a	126 b	168 a	176 a	165 a
Chisel till‡	–	–	174 a	120 a	126 b	168 a	176 a	165 a
Org2	72 b	56 c	120 b	38 c	69 c	78 b	121 c	71 c
Org3‡	–	81 b	120 b	60 b	71 c	52 c	144 b	73 c
Org4+‡	–	–	167 a	109 a	226 a	74 b	121 c	115 b
N source¶								
No till	F + V	F	F	F	F	F	F	F
Chisel till‡	–	–	F	F	F	F	F	F
Org2	V	V	V + M	V	V	M	M	M
Org3‡	–	V	V + M	V	V	M	V + M	V
Org4+‡	–	–	H + M	A	H + M	A	M	A + M

† Values within a year for a given variable followed by the same letter are not significantly different at $P < 0.05$.

‡ Values in 1996 and 1997 are omitted for chisel till, which was managed with reduced inputs, and for Org3 and Org4+ when the rotation was not fully established.

§ Estimated available N inputs for organic systems were determined by dividing green manure N content by two, adding underground N contribution for perennials, and adding manure N availability as described in the text when appropriate.

¶ F = fertilizer, V = vetch or vetch mix, M = animal manure, H = mixed hay (red clover and orchardgrass), A = alfalfa

to replace a stand that died in fall 2003 as the result of prolonged wet soil conditions earlier that year.

Manure provided an estimated 40 to 193 kg available N ha^{-1} (mean = 93 kg available N ha^{-1}, for those years when manure was applied). The range of estimated available N inputs when both green and animal manures were applied was 115 to 226 kg N ha^{-1} (mean = 149 kg available N ha^{-1}). Estimated N availability varied by year and by system, with N inputs being greater in Org4+ than in Org2 and Org3 in four of 6 yr and with N inputs being greater in NT and CT than in Org4+ in 3 of 6 yr (Table 5).

Corn Ear Leaf Nitrogen

The sufficiency level for corn ear leaf N is 2.70% (Mills and Jones, 1996). Our data suggest that N was always adequate in conventional systems except perhaps in NT in 1997 (Table 6). Corn in at least one of the organic rotations showed signs of N stress in all years that ear leaf N was sampled and was almost always lower than in conventional systems with the notable exception of 2002 (Table 6), a dry year with very low corn yields especially among organic systems (Table 2). There were strong relationships between estimated available N inputs and corn ear leaf N in all years that both parameters were measured except 2002 (Table 6). Since ear leaf N, and the surrogate measure, ear leaf chlorophyll, is a poor measure of corn performance (N uptake and yield) in dry years (Eghball and Power, 1999), we evaluated the relationship between estimated available N inputs and corn ear leaf N only for years with adequate rainfall (1996, 2000, 2001) using regression analysis. Nitrogen inputs were strongly associated ($r^2 = 0.74$, $P < 0.0001$) with ear leaf N in these years according to the equation,

$$\mathrm{ELN} = 0.0116\mathrm{N} + 1.26,$$

where ELN is ear leaf N (%) and N is estimated available N inputs (kg ha^{-1}). This equation indicates that, in good years, 124 kg N ha^{-1} is necessary to provide sufficient N to corn (i.e., ear leaf N = 2.70%) at this site. Nitrogen inputs in the organic systems were often <124 kg ha^{-1} (Table 5), suggesting that corn in the organic systems was often N-limited because of relatively low N inputs. Since estimated available N inputs and

Table 6. Corn ear leaf N and coefficients of determination for correlations between estimated available N and ear leaf N. The Org2, Org3, and Org4+ are, respectively, 2-, 3-, and 4- to 6-yr organic crop rotations.

	Corn ear leaf N				
System	1996	1997	2000	2001	2002
			%		
No till	3.54 a†	2.61 a	3.27 a	3.09 a	2.88 c
Chisel till‡	–	–	3.21 a	2.88 a	2.99 bc
Org2	2.13 b	2.11 b	2.72 b	1.85 bc	3.13 ab
Org3‡	–	2.48 a	2.65 b	1.51 c	3.24 a
Org4+‡	–	–	3.11 a	2.21 b	2.62 d
R^2	0.77**	0.72*	0.82***	0.59§	ns¶

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

† Values within columns followed by the same letter are not significantly different at $P < 0.05$.

‡ Values between 1996 and 1998 are omitted for Chisel till, which was managed with reduced inputs, and for Org3 and Org4+ when the rotation was not fully established.

§ $P < 0.0001$.

¶ ns = not significant.

Table 7. Least-squared means of corn and soybean yields and associated explanatory variables over the optimum 5 yr for crop growth (1996, 2000, 2001, 2004, and 2005) at the FSP site. The Org2, Org3, and Org4+ are, respectively, 2-, 3-, and 4- to 6-yr organic crop rotations.

	Corn				Soybean	
System	Weed cover	N Inputs	Population	Yield	Weed cover	Yield
	%	kg ha^{-1}	no. ha^{-1}	Mg ha^{-1}	%	Mg ha^{-1}
No till	17 c[†]	165 a	57,100 a	9.78 a	1 b	4.67 a
Chisel till	3 d	166 a	57,700 a	9.98 a	1 b	4.40 a
Org2	44 a	84 c	55,000 a	6.72 d	26 a	4.03 b
Org3	30 b	96 c	56,000 a	7.45 c	29 a	4.04 b
Org4+	22 bc	120 b	56,800 a	8.16 b	21 a	4.04 b

[†] Values within columns followed by the same letter are not significantly different at $P < 0.05$.

corn ear leaf N were strongly correlated in our study and since we collected ear leaf N data in only a limited number of years, we used N input data instead of ear leaf N data in subsequent analyses described below.

Yield Dependence on Weed Cover, Nitrogen Inputs, and Population

Corn yield during years with normal rainfall—1996, 2000, 2001, 2004, and 2005—was negatively related to weed cover ($P < 0.0001$), and positively related to N inputs ($P < 0.0001$) and corn population ($P = 0.0002$) when each variable was tested individually using a first order model. When these three variables were included together in a multiple regression model, all terms were significant ($P \le 0.001$). The final regression model was

$$Y = 1780 - 20.0C + 27.8N + 0.064P \qquad [1]$$

where Y is corn yield (kg ha^{-1}), C is weed cover (%), N is estimated available N input (kg ha^{-1}), and P is corn population (number ha^{-1}). This model shows that corn yield was independently affected by each of these three variables when adjustment was made for the effect of the others.

Averaged over these 5 yr, corn yields in Org2, Org3, and Org4+ were 33, 25, and 18% lower, respectively, than in CT (Table 7). The trend of increasing corn yield with increasing rotation length among the organic systems mirrored the trend of lower weed cover and increased N inputs as organic rotation length increased (Table 7). In contrast, corn population was similar among all systems on average across these 5 yr (Table 7).

When corn yield during these 5 yr was subjected to analysis of variance with system as a class variable, there was a strongly significant system effect ($P < 0.0001$). When corn yield was subjected to analysis of covariance with system as a class variable and weed cover, N inputs, and corn population as regression variables, system was no longer significant ($P = 0.25$). These results suggest that all of the significant differences between systems could be explained by weed cover, N inputs, and population.

Equation [1] also can be used to determine the relative impact of weeds, N, and population on lowering yield in the organic systems relative to the conventional systems in these years. Values for weed cover, N inputs, and corn population from Table 7 were plugged into the multiple regression model (Eq. [1]). The resulting values for the weed, N, and population terms of the model were tracked separately and values associated with each of the organic systems were subtracted from those of CT to determine the impact of each model term on the overall yield differences between the organic and CT systems (Table 8). Lower N inputs in organic systems accounted for 70 to 75% of the differences in corn yield between organic systems and CT whereas higher weed cover accounted for 21 to 25% and lower corn population accounted for 3 to 5% of these yield differences (Table 8).

Table 8. Partitioning of the corn yield difference between organic and chisel-till cropping systems amongst weed competition, lower N availability, and reduced corn population. The Org2, Org3, and Org4+ are, respectively, 2-, 3-, and 4- to 6-yr organic crop rotations.

	Model estimation				
System	Weeds	Nitrogen	Population	Total	Harvested total
Yield reduction, kg ha^{-1}[†]					
Org2	820	2280	170	3270	3260
Org3	540	1950	110	2600	2530
Org4+	380	1280	60	1720	1820
Contribution to total estimated yield reduction, %[‡]					
Org2	25	70	5		
Org3	21	75	4		
Org4+	22	75	3		

[†] Model yield reduction estimates were computed by inserting mean values for weed cover, N inputs, and corn population presented in Table 7 into Eq. [1] for each system and then subtracting values for the organic systems from the corresponding value for the chisel-till system.

[‡] Percentage of estimated component yield reduction relative to estimated total yield reduction.

Full-season soybean yield was also significantly ($P < 0.0001$) higher in conventional than in organic systems averaged over these same 5 yr (Table 7). Regression analysis demonstrated a significant effect of weed cover on soybean yield over these years ($P < 0.0001$) where yield was reduced by 17.5 kg ha^{-1} for every 1% increase in weed cover. When an analysis of covariance was performed with system as class variable and weed cover as regression variable, soybean yield was no longer significantly affected by system ($P = 0.11$). These results suggest that differences in soybean yield between conventional and organic cropping systems could be explained solely by differences in weed abundance in these systems.

CONCLUSIONS

In this long-term study, corn and soybean, but not wheat yields were generally greater in conventional than in organic systems. There were few significant differences in corn yield between CT and NT but corn yield among organic systems generally increased with increasing crop rotation length and complexity. Average corn yield in Org2, Org3, and Org4+ was 41, 31, and 24%, respectively, lower than in CT across years in which all systems were present (2000–2005). The proportional corn yield loss in organic systems, however, tended to be greater in years with less-than-optimum conditions than in years with good growing conditions. Multiple regression analysis showed that low N availability explained 70 to 75%, weed competition explained 21 to 25%, and plant population explained 3 to 5% of lower corn yields in organic than in conventional systems. Covariance analysis showed that these three variables accounted for all significant differences in corn yield among systems.

For soybean, there were few differences in yield between the two conventional systems or among the three organic systems but yield in the conventional systems was often greater than in organic systems. Average soybean yield in the organic systems was 19% lower than in CT in years that all systems were present (2001–2005). Regression analysis suggests that weed competition alone accounted for the difference in soybean yield between organic and conventional systems. Wheat yields, on average, were similar in all systems. There was little effect of crop rotation length and complexity on soybean and wheat yields among organic systems.

These results highlight the challenges inherent in providing adequate N for corn when relying solely on organic sources in the mid-Atlantic region. Green manure crops alone often do not provide adequate N and use of animal manures, which generally have more P than N relative to crop needs, is often limited on high P soils, which are common in the mid-Atlantic and other regions. Results also highlight some of the challenges and options for controlling weeds in organic systems. Wet soil conditions often limited the ability to conduct timely weed control tillage operations and weeds within the row often were not adequately controlled even with timely operations. Alternatively, a minimum tillage system that relied on weed suppression with surface cover crop residue also was inadequate. However, increasing crop rotation length and crop phenological diversity with fertility building cover crops and hay crops, can help reduce weed competition by reducing annual weed population levels and also enhance yields of high-N requiring crops such as corn. A hay crop in the rotation may also reduce the overall tillage used in organic systems while still allowing tillage for row crops. Future research should be aimed at developing more effective integrated organic management systems that reduce tillage while building adequate fertility and reducing the competitiveness of weeds.

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