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B843: The Ecology, Economics, and Management of Potato Cropping Systems: A Report of the First Four Years of the Maine Potato Ecosystem Project

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A Report of the First Four Years of the Maine Potato Ecosystem Project

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MAINE AGRICULTURAL AND FOREST EXPERIMENT STATION
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The Ecology, Economics, and Management of Potato Cropping Systems: A Report of the First Four Years of the Maine Potato Ecosystem Project

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Dedication

The members of the Maine potato ecosystem research group dedicate this publication to Wallace C. "Wally" Dunham, past Dean of the College of Applied Sciences and Agriculture and Director of the Maine Agricultural Experiment Station. He hired each of us, he displayed courage in establishing our group, he provided the initial funds, the land, and the facilities, he maintained trust and belief in our abilities and motives, and he gave us his encouragement and blessings throughout. He was our mentor.

And we ask the readers to think of our students when reading this publication, for it is their commitment to the principles of ecologically balanced and environmentally sensitive agriculture and their steadfast pursuit of knowledge that provide us with both a guiding inspiration and a purpose beyond our own.

Michele C. Marra, Editor

Barbara A. Harrity, Technical Editor

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Foreword

A. Randall Alford

> Knowing in part may make a fine tale, but wisdom comes from seeing the whole (Young 1992).

During the mid-1980s, a group of undergraduates from various agricultural science curricula at the University of Maine began promoting an academic major in sustainable agriculture. Representatives of the student group met first with a few faculty members who were teaching courses and conducting research in areas the students found appealing and appropriate to their cause, and a coalition was formed to carry the idea through the administration. The group met with Dean of the College of Life Sciences and Agriculture and Director of the Maine Agricultural Experiment Station Wallace C. Dunham, and he, along with his Associate Dean of Instruction, began to explore the concept. It was decided that the potential value and merit of the program to the College and the Experiment Station were significant and justifiable. In 1986, a new faculty position was created with primary responsibility as coordinator of the sustainable agriculture academic program. Over the following several months, faculty members were recruited from departments throughout campus, a curriculum was formed of new and existing courses, and students entered the program in the fall of 1987. This marked the establishment of the first academic major in sustainable agriculture at a land-grant university in the United States.

In November of 1987, participating faculty and associates from Cooperative Extension and USDA-ARS met to discuss the opportunities for multidisciplinary research, with the objective of integrating the sustainable agriculture concepts of the classroom into an ecosystem-level project. After much deliberation and consideration of such factors as crop acreage, existing infrastructure and support, current research and extension activities, and researchable components of production practices, the group identified potatoes as the commodity of focus. A project description was developed, which was characterized by a long-term study of alternative crop management strategies and included each discipline represented in the discussions.

The scientists brought the project to the Director of the Experiment Station, and he asked that the potato industry be included in an advisory capacity, and during the winter of 1988, the proposal was presented to a group of industry representatives through the Maine Potato Board. The specifics of this early project proposal included such aspects as extended rotations, livestock, and on-farm studies, which are not components of the existing study because of these early discussions. Over the next year, significant modification of the project occurred, each change in direct response to industry concerns over the applicability of the proposed investigation. The result of this dialogue was a project that gained the support of the Experiment Station Director and the Maine potato industry, included scientists from five academic departments, and established the commitment of the University of Maine to conducting research on the principles of sustainable agriculture and how they would be applied to potato cropping systems.

The Experiment Station had just acquired a farm with an extensive history of commercial potato production, and this farm as the experimental site and five years of base funding through the USDA-CSRS Special Grants Program were obligated to the project by the Director in early 1990. For the 1990 growing season, the entire site was planted with millet, and soil samples were analyzed to aid in the assessment of land quality so that research plots could be established. Discussions of experimental design continued throughout the next several months, and the project was initiated in the spring of 1991. The project personnel during that first growing season included seven research scientists, eight graduate students, six undergraduate field assistants, and a site manager. The project has grown incrementally over each year, and during this past year 35 persons worked on site.

Over these five years, the impact of the potato ecosystem project has been significant in many areas of the University. Extramural funding of studies directly associated with the large-scale project now exceeds base funding. Other projects have been developed that link critically to our understanding of the potato ecosystem and its management, such as the Aroostook Soil and Water Management Project and the USDA-CSRS Potato Blight program. The reputation of the project has led to many invited presentations by participants to a range of audiences, including scientific organizations, commodity groups, and Cooperative Extension workshops. Also, the research site has been visited by many interested groups and individuals, and this has provided an infusion of ideas and perspectives from literally around the world. The success of the project has provided an exciting and realistic tool for the recruitment of highly qualified and motivated faculty, professionals, and undergraduate and graduate students. The Maine potato industry has become our greatest ally, thereby supporting the relevance of our efforts to the users. The MAFES potato ecosystem project is now acknowledged as one of the most comprehensive and progressive approaches in the world to the ecologically based, biologically efficient, and economically profitable management of an agricultural commodity.

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I. Introduction

Michele C. Marra

AGRICULTURE AND THE ENVIRONMENT

There is much current debate about the extent to which agricultural production affects the environment and about how to mitigate the effects. Regulations, at both the state and federal level, on the chemicals farmers can apply and the manner in which they can apply them are being refined and upgraded continually as new scientific information appears. There is also growing concern about the negative impact that current farming practices may have on soil productivity in some areas of the country and on increased pesticide resistance of some key regional agricultural pests. These two factors can lead to more reliance on chemical inputs to maintain output. Table 1.1 illustrates the national trends in pesticide use. Pesticide use has increased in the U.S. more than twofold since the mid-1960s, with agriculture's share of total use rising as well (Table 1.1). As this reliance increases, costs of production are likely to rise faster than commodity prices in these regions, thus decreasing farm profits. The long-term economic sustainability of the agricultural industry as a whole and the rural economies in those regions that depend on agriculture may then be in jeopardy. Policy makers, scientists, and the agricultural community are seeking solutions to these growing problems. In the current climate, more stringent regulation of agricultural chemicals seems likely, making the search for sustainable solutions even more important.

Table 1.1. United States pesticide use, total and estimated agricultural share, 1964–1988.

Year	Total U.S.	Agricultural Sector	
	------ million lb ai[a]	--------	%
1964	540	320	59
1970	740	430	58
1975	990	625	63
1980	1,175	846	72
1985	1,112	861	77
1986	1,096	820	75
1987	1,085	815	75
1988	1,130	845	75

[a] ai=active ingredient

Source: Cline et al. (1990)

THE FARM ECONOMY IN MAINE

Potato production has been the leading agricultural output in Maine for decades. Figure 1.1 shows the relative value of potato production in Maine in 1992. Once a healthy and growing sector of the farm economy, the potato industry has suffered many setbacks in recent years. Potato acreage in Maine in the late 1960s approached 160,000 acres, but has fallen to just over half that in recent years (Figure 1.2). Potato production has fallen at the same rate (Figure 1.2). The result of all of this is a steady decrease in potato farm numbers in Maine (Figure 1.3). Northern Maine, so long dependent on the potato industry as a major contributor to its economy, has seen significant negative effects of this decline. It seems, then, that finding ways to enhance the long-term sustainability of the potato industry would also contribute a great deal to the economic health of a large portion of the state.

One proposed solution to these problems is to take a "systems approach" to agricultural production. By capitalizing on certain features of the natural biological system in which production takes place, a systems research approach may identify alternative management systems that have less reliance on chemical inputs than current systems while maintaining or enhancing the economic viability of farms. The systems approach to farming requires improved information about the biological and physical relationships within the production environment, and the ability to manage those relationships advantageously.

To this end, a group of University of Maine researchers came together in the late 1980s to discuss possible courses of action. Developing from these early meetings is the cropping systems study described in this bulletin. Stated formally, the objectives of the project are

1. to study the impact of nutrient management, soil amendments, soil properties, insect damage, weed competition, and cropping system management on potato and rotation crop productivity and on nutrient and chemical dynamics;
2. to describe the interactions between soil fertility, plant vigor, and the behavior and natural mortality of insect pests and beneficial species;
3. to determine the effects of crop rotation, soil amendments, and weed management systems on the abundance and species composition of weed seeds in the soil and weeds growing in potatoes and rotation crops; and

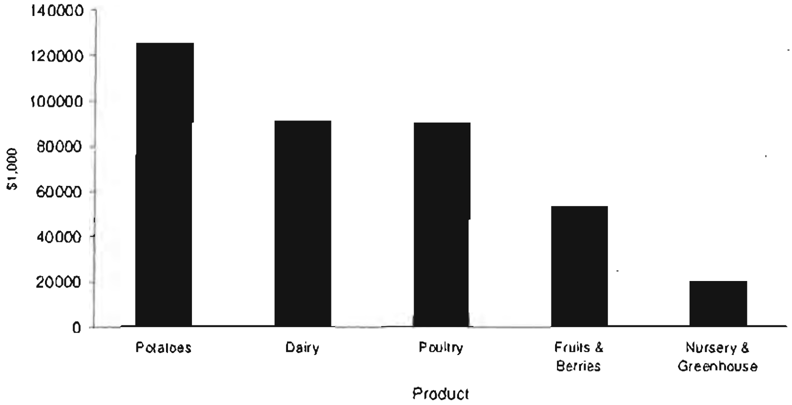

Figure 1.1. Market value of the top five agricultural products in Maine, 1992. Source: USDA (1994)

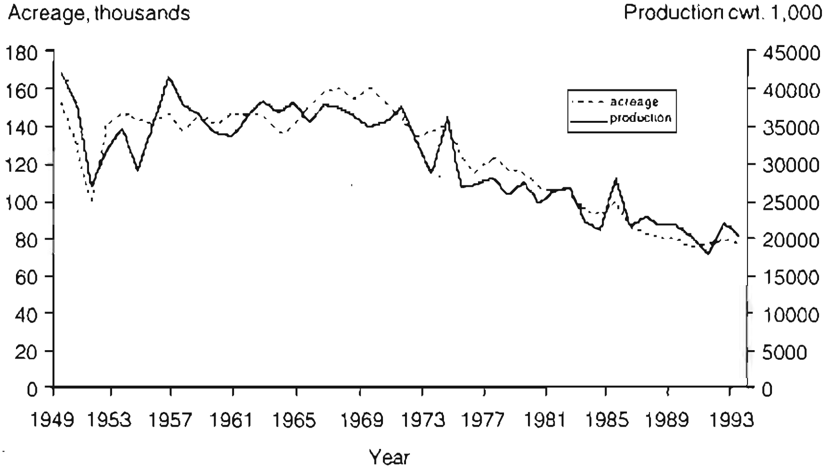

Figure 1.2. Potato acreage and production in Maine, 1949–1993. Source: USDA (1994).

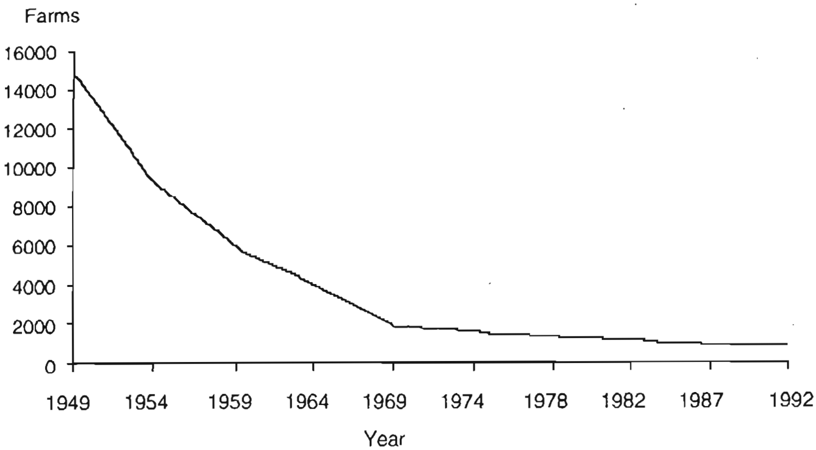

Figure 1.3. The number of potato farms in Maine over time. Source: USDA (1994).

4. to analyze the economic consequences of the alternative potato cropping strategies developed from information gathered in Objectives 1 through 3.

The study team has now completed four years of experiments (two complete rotations) and collected a large amount of useful information. This bulletin describes the study and presents the results to date and our interpretation of them. These results are preliminary because most of the relationships cannot be firmly established with only four years' data, and the reader is cautioned not to draw firm conclusions about which production strategy is "best."

We hope the results of this study will provide valuable information to producers as they choose, or are required by further regulation, to change their production strategies in favor of lower chemical inputs. We begin with a general description of the study and then turn to a more detailed discussion of each aspect of the potato cropping system being examined.

GENERAL DESCRIPTION OF THE STUDY

The study site is a 15-acre tract on the northern boundary of the University of Maine's Aroostook Farm Research Center in Presque Isle, Maine. The 96 main plots are approximately 15% of an acre each, which provides a larger scale than would most research plots.

The main plots are grouped into four blocks. Each block is an area of land where soil survey data show similar soil characteristics. Thus, given the same production inputs, the crop output is expected to be the same on each plot within a block. This is done so that observed differences in crop output, or any other measure taken in the plots within the block, can be attributed to the different inputs applied, instead of to differences in initial soil characteristics. Within each block there are 24 plots to which the different treatments have been randomly assigned. A treatment is a particular combination of the following factors:

1. Pest management—conventional, reduced input, biological

   Conventional (CONV)—Pest control was accomplished with synthetic pesticides using current recommendations from University of Maine Cooperative Extension specialists. Insecticide applications were based on published economic threshold values.

   Reduced Input (RI)—Pest control was accomplished with synthetic pesticides applied at lower rates or decreased frequency compared to the CONV system. Insecticide applications were based on double the economic thresholds used in the CONV system.

   Biological (BIO)—Biological agents and cultural practices were used to control pests. The timing and amount of control agents were based on the recommendations of the research team. The inputs used from 1991 to 1994 changed as experience was gained.

   A change made after the 1991 crop year was that the pest management decisions were based on pest density information for each plot instead of on average densities for all plots in each pest management treatment. Therefore, each plot can be thought of as a separate farm field on which pest management decisions are made and which potentially can receive a unique set of inputs in any one year.

2. Potato variety—Atlantic, Superior

   Atlantic was chosen to represent a mid-season, disease-tolerant, round-white variety.

Superior was chosen to represent an early-season, disease-susceptible, round-white variety.

3. Soil management—amended, unamended

   The amended treatment received large quantities of organic materials through the use of beef manure, compost, and a green manure rotation crop (a mixture of pea/oat/vetch). The unamended system did not receive manure or compost and included a cash grain (barley) rotation crop intercropped with red clover (see Appendix Table A3).

   Amended treatments were given a reduced rate of chemical fertilizer (about half the recommended rate). In the BIO plots, only the compost and manure were used as nutrients in 1992, with no chemical fertilizer applied. The reduced rates of fertilizer were used in the BIO and other pest management treatments in 1991, 1993, and 1994.

   Unamended treatments for the CONV and RI pest management plots received the recommended rate of chemical fertilizer. These plots in the BIO pest management treatments received no chemical fertilizer in 1992 and the recommended rates in 1991, 1993, and 1994.

Barley was grown in the rotation crop plots for all pest management systems in 1991. In the CONV and RI plots during 1992, the rotation crop was barley, but in the BIO system, green manure (consisting of a mixture of peas, oats, clover, and vetch) was grown in 1992 preceding the 1993 potato crop. Beginning in 1994, all plots receiving the amended treatment had followed the green manure crop. The rotation crops also received the various pest management and soil management treatment combinations (excluding manure applications).

In any one crop year, half the plots in each block were planted to potatoes and half were planted to the assigned rotation crop. Each potato plot receives one of the twelve possible treatment combinations (three pest management treatments × two varieties × two soil management treatments), and each treatment combination is repeated once in each block for a total of four replications. Appendix A contains more detailed information about the study design. The following sections provide details of the major aspects of the study based on the first four crop years.

A vital feature of the potato ecosystem project is the component study approach, a designated area occupying half of the tillable land, where short-term experiments are conducted to extensively examine specific treatment interactions occurring within the larger study site. Each year in the component study site there are several of these experiments on-going, each for two- to three-year durations. Most often graduate student research is conducted here. Examples of past and current experiments are given in Table 8.1.

Table 1.2. Component studies conducted in association with MAFES potato ecosystem project.

1. Interaction of soil fertility, plant quality, Colorado potato beetle (CPB) vigor, and CPB insecticide susceptibility.
2. Effects of nitrogen fertilization on CPB growth, development, and economic injury level.
3. Biology and seed predation of the adult and larval ground beetle *Harpalus rufipes* in potato and barley.
4. Effects of the potato ecosystem landscape structure on the dynamics of the seven-spotted ladybeetle,
5. Modeling *Beauveria bassiana*, a fungal disease of CPB.
6. Biomass production, nitrogen accumulation, and radiation use efficiency of pea, oat, and vetch green manure mixtures.
7. Effects of moldboard and chisel plowing on weed dynamics in barley-potato and oat-pea-vetch green manure -potato rotations.
8. A production function approach to factor analysis in agroecosystems.
9. Legume green manure rotation crop effects on potato yield and nitrogen uptake.
10. Nitrogen and CPB effects on potato growth, nitrogen uptake, and yields.
11. Rate effects of cull potato compost on soil properties, nutrient uptake, and yields.
12. Soil management and supplemental water effects on potato crop root and haulm growth, tuber nutritional attributes, and yield.
13. Nitrogen leaching-cover crop study

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II. Crop and Soil Research

Gregory A. Porter and Jeffrey C. McBurnie[1]

INTRODUCTION

Potato production in Maine and the Northeast is frequently chemical intensive (e.g., six or more fungicide applications and three or more insecticide applications per year, plus average chemical fertilizer rates of 165, 177, and 177 lbs/A, respectively, of nitrogen, phosphate, and potash) and often promotes degradation of soil resources due to intensive cultivation and short cropping cycles (ERS 1992; Hepler et al. 1984, 1985; Westra and Boyle 1991). This project examines several pest and soil management approaches as alternatives to conventional, chemical-intensive potato production approaches. If commercial potato producers are to seriously consider alternative management systems, it is important that information is available on the effects of these systems on the growth, the yield, and the quality of all crops within the crop rotation. This project represents a key step toward obtaining such information.

To reverse the detrimental effects of potato production on soil productivity, management practices are needed that will return large amounts of decomposing organic residues. Such additions have the potential to improve soil water-holding capacity and aeration (Saini 1976; Stevens and Hammond 1992). The alternative soil management system under study within this project adds large amounts of organic matter and plant available nutrients into a typical potato soil. This system is contrasted with a conventional system, based on chemical fertilizers and few organic matter inputs. These soil management systems would be expected to differentially affect soil nutrient concentrations, soil physical properties, and crop nutrient uptake. If this research can establish that these soil properties are dramatically improved by short-term application of composts and manures, the productivity of potato production systems in Maine and the Northeast might be enhanced, while reducing negative effects due to runoff and drought.

The major objective of this portion of the Potato Ecosystem Study was to document the effects of the pest and the soil management systems on crop growth, yield, quality, and nutrient uptake, and to monitor the effect of differential management on selected soil properties. Several measures of crop growth and productivity

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[1] Special thanks go to Mac Brown, Leslie Ferris, and Jonathan Sisson for their fine work in the field.

were conducted for the various crops in the system; however, special attention was focused on the potato crop, the major cash crop in this production system. Because the management systems were expected to affect both nutrient availability and yield, we measured nutrient concentrations of the potato crops and removal of plant available nutrients from the system. Soil analyses centered on standard monitoring of soil nutrient concentrations, as well as several key physical properties (e.g., organic matter content, bulk density, soil structure, and water retention properties).

METHODS

Potato Crop

Plant stand, leaf area index, and foliage vigor

Emergence of the potato crop was documented by counting the emerged plants in two flagged 30-ft lengths of row located within each potato plot. These counts were conducted two to three times weekly. The crop was assumed to have reached its final crop density when the counts became constant. At this time, final stand counts were taken on the entire lengths of the four center rows of each plot. Percent stand was calculated from these data and the number of plants expected per row.

Plant canopy growth was documented by nondestructively estimating leaf area index (LAI) at several dates during each growing season. These estimates were made with a LAI-2000 plant canopy analyzer (Li-Cor Instruments, Lincoln, NE) at two locations within each plot. Percent ground cover was visually estimated at the approximate date of maximum ground cover during July and/or August of each growing season. Foliage vigor ratings were taken at these times and just before vine destruction to qualitatively monitor the condition of the plots within the varied pest and soil management systems.

Biomass sampling and nutrient analysis

Leaf and petiole samples were collected at one or more dates during each growing season. For either type of sample, 30 recently expanded leaves were collected, generally the fourth or fifth leaves from the top of the plants. For petiole analysis, the leaflets were stripped from the petioles, dried at 140°F, ground, and analyzed for nitrate-nitrogen content using the method described by Porter and Sisson (1991). For leaf nutrient analysis, the leaves were washed in deionized water, dried at 140°F, ground, and submitted to the University of Maine Analytical Laboratory for nutrient analysis.

Biomass yields of haulms and tubers were determined just before vine desiccation by removing eight randomly selected plants per plot. The plants were separated into haulms and tubers, washed, weighed, and subsampled. The subsamples were weighed, dried, and re-weighed so that dry matter biomass yields could be calculated. Dried haulm and tuber samples were then ground and submitted to the University of Maine Analytical Laboratory for nutrient analysis.

Determination of potato yield and quality

Yields in the potato crop were determined from the four center rows of each plot (25% of each plot area). These rows were dug with a two-row potato digger, and tubers were collected by hand. The yield of the entire four rows was weighed in the field. Where tuber rot was prevalent, any decaying tubers were weighed separately in the field. Two 50-lb subsamples were taken from the yield rows of each plot for quality evaluations. These samples were graded for external defects (i.e., sunburn, off-shapes, growth cracks, scab) and then sized on a spool-type sizer. Weight of tubers in six individual size classes was recorded. Data from several of these size classes were later combined for presentation. U.S. #1 yields were calculated as yield of tubers between 1⅞ in. and 4 in. diameter, after removing those with external defects. Specific gravity was determined on a 10-lb subsample using the weight-in-air/weight-in-water method. Once the yield rows were removed, the remaining 12 rows of each plot were harvested with a conventional, two-row potato harvester. Dates of important cultural practices and harvest for each year are reported in Appendix Table A2.

Rotation Crops

Barley crop sampling

Barley planting and harvest dates are provided in Appendix Table A5. Six quadrat samples (5.4 ft^2 each) were collected from each barley plot before combining to determine aboveground biomass production. Two 59-in.-wide swaths (0.0152 acres each) were harvested from each plot with a small-plot combine to determine grain yield. The grain and biomass samples were used to determine grain and straw yield. Subsamples of each were dried, ground, and submitted to the University of Maine Analytical Laboratory for nutrient analysis. The nutrient analysis and yield data allowed us to calculate crop nutrient removal by the barley crop, and also the amount of nutrients returned to the soil by the straw.

Green manure crop sampling

Green manure planting and harvest dates are provided in Appendix Table A5. Six quadrat samples (5.4 ft^2 each) were clipped at the soil level and collected from each plot during October of each year to determine final, aboveground biomass yields by each species in the mixture. Three of the quadrat samples were pooled to create a single aggregate yield sample. The remaining three quadrat samples were sorted into separate categories representing the individual crops in the mixture and into an additional category for total weed biomass. A representative subsample of the aggregate green manure mixture was dried, ground, and submitted to the University of Maine Analytical laboratory for nitrogen analysis. The nutrient analysis and yield data allowed us to calculate the aboveground nitrogen content of the green manure crop.

Soils

Soil sampling and nutrient analysis

Ten soil cores were collected to a 9-in. depth prior to planting in the spring of 1991. These cores were bulked, mixed, and a single sample was removed to represent an entire plot. These samples were dried, sifted, and submitted to the University of Maine Soil Testing Laboratory for determination of pH and mineral nutrient content using standard methods. Effective cation exchange capacity was estimated using the sum of cations procedure and buffer pH values. This sampling procedure was repeated in the fall of 1991 and subsequent growing seasons, so we could measure the effects of management systems on general soil fertility as the experiment progressed over time.

Additional soil samples were collected and used to measure inorganic nitrogen levels within the soil. Using a soil probe, ten to 15 soil core samples were collected per plot, composited in a clean plastic bucket, mixed, and then placed in a sample dryer at 140°F for 24 hr. A subsample was taken and sent to the Maine Soil Testing Laboratory for analyses of nitrate (NO_3^-) and ammonium (NH_4^+) nitrogen. These ions were extracted using KCl and analyzed via standard methods.

Soil organic matter content

Soil samples were collected to a 6-in. depth prior to organic amendment application each spring. Ten subsamples were collected from each plot and were bulked and mixed thoroughly. Duplicate subsamples from each bulked sample were analyzed for readily oxidizable organic matter using the Walkley-Black method (Nelson and Sommers 1982).

Soil physical properties

Measurements of water-stable soil aggregate content were initiated during 1991 along with attempts to sample soil solution with suction lysimeters. More extensive evaluation of soil physical properties began in 1993 as a result of unsuccessful attempts to measure and to monitor the quality of soil water via vacuum lysimeters in 1991 and 1992. Existing soil moisture conditions made it practically impossible to collect consistent water samples during the growing season. We decided to focus on the impacts that soil amendments might have on other soil properties. Effects on soil water, and potentially ground water, could be inferred from these results and the inorganic nitrogen analyses. Variables measured beginning in 1993 included gravimetric moisture content of the surface soil, soil bulk density, and water retention.

Water-stable aggregate content of the soil was quantified as a measure of soil structure. This analysis was conducted on one pooled sample from each plot. Each sample consisted of ten soil slices collected to a 6-in. depth before tillage each spring. These slices were collected when the soil had a moisture content that was appropriate for tillage operations and in a manner that minimized structural disturbance. The slices were bulked within plots, air dried, and passed through a ¼-in. sieve with care taken not to crush soil aggregates. Sample analysis was accomplished using a series of nested sieves with appropriate sized openings. Our sieves allow categorization of aggregates into three size classes: (1) large (0.08 to 0.25 in.); (2) medium (0.04 to 0.08 in.); and (3) small (0.01 to 0.04 in.). Individual soil samples, approximately 0.35 oz each, were placed on the upper sieve, wetted for ten minutes, and then sieved for ten minutes. The dry weight of soil in each aggregate size class was determined. The sample was then dispersed using sodium hexametaphosphate and mechanical mixing. The dispersed sample was re-sieved to determine sand content. Percent water-stable aggregates in each size class was determined as 100 × [(weight of aggregated soil in the size category - weight of sand)/(total weight of soil - weight of sand)]. Duplicate subsamples from each plot were analyzed.

Soil bulk density was determined using the soil core method (Blake and Hartge 1986). A cylindrical sleeve with removable sample cylinders of known volume was driven into the ground after surface debris had been removed. The core was pulled from the ground, the sample cylinder was taken from the sleeve, and the ends were trimmed with a large, sharp spatula. Cylinders were then capped and taken to the laboratory to be weighed. As long as the soil has moderate moisture content, the sample should be relatively undisturbed and therefore representative of the soil in-situ. Each sample was weighed before drying; this information was used in moisture content determinations. The samples were dried in a convection drying oven at 221°F and were then re-weighed. The dry weight, adjusted for the cylinder weight, divided by the cylinder volume yielded the sample bulk density. Two samples per plot were taken and the results averaged.

Within the reduced input (RI) pest management system, gravimetric moisture content was measured from samples collected in the surface soil to a 9-in. depth. Ten soil cores were collected from between the potato rows, composited, mixed, and subsampled. The samples were then weighed, dried in a forced-air oven, and re-weighed. The dried samples were sieved to remove coarse fragments with a diameter greater than 0.08 in. Weight of these fragments was subtracted from both wet and dry weights during the calculation of percent soil moisture content. Gravimetric moisture data will not be presented in this report.

Pressure extraction units were used to develop the moisture retention (drying) curves (Klute 1986; Soil-moisture Equipment Corp. n.d.) for disturbed soil samples. The samples were taken as subsamples of ten to 15 soil probe samples, which were composited. Particles greater than 0.08 in. were removed, but care was taken to provide minimal disturbance of soil aggregates. Each sample was divided into five to seven subsamples, one sample per extraction pressure. Two extraction units were used: a low pressure (0–500 kPa) and a high pressure (0–1500 kPa). Four low-pressure (100 kPa) and three high-pressure (1500 kPa) plates could be used simultaneously. Up to 12 samples per plate were tested. Plates were soaked overnight before use. Approximately 0.88 oz of soil was placed in plastic cylinders 0.4 in. deep and 2.07 in. in diameter, which rested on the saturated pressure plates. Additional water was added to the plates and the samples soaked for 24 hr to ensure saturation. Plates were then placed in the extraction units and pressure was applied. After the units equilibrated (i.e., water was no longer being extracted), the top plates (one per unit) were removed, samples were weighed and put in the oven to dry (24 hr @221°F), and pressure was increased in the units. This process was repeated until the maximum pressure had been reached and all plates had been removed. Dried samples were weighed and gravimetric moisture contents were determined by standard methods.

Statistical Analyses

Statistical analyses were conducted via SAS (SAS Institute) using the ANOVA and GLM procedures. F-tests within the analysis of variance were used to test hypotheses about treatment effects. Where needed, comparisons between means were conducted using Fisher's LSD test.

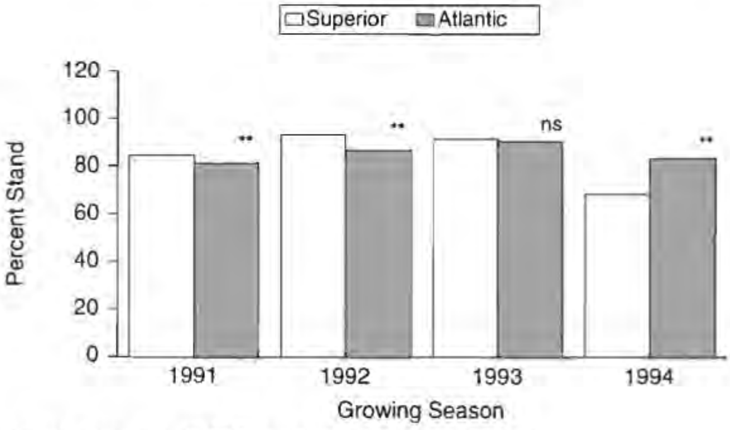
RESULTS AND DISCUSSION

Potato Crop

Plant emergence and stands

The rate of crop emergence was not measured during 1991; however, final plant stands were determined during early July. Plant stands averaged 82% of target stands and were not significantly affected by pest or soil management system. Final percent stand of Superior was significantly higher than Atlantic (Figure 2.1).

Superior emerged significantly faster than Atlantic during 1992 (data not presented). At the 15 June 1992 rating date, Superior had reached 57% emergence while Atlantic was only 31% emerged ($p<0.01$). A similar difference existed four days later (81.5% vs 64.9%, $p<0.01$). Throughout emergence during 1992, the conventional pest management system (CONV) displayed the fast-



Target populations were 18,735 plants per acre (9.3-in. spacing)
Significant difference ($p<0.01$) between varieties noted by **.

Figure 2.1. Percent crop stands, 1991–1994 (averaged over pest and soil management systems).

est emergence, while the biological system (BIO) was slowest and the reduced input system (RI) was intermediate. For example, percent emergence on 17 June 1992 was 66.9%, 51.0%, and 43.0%, respectively, for CONV, RI, and BIO. CONV emergence was significantly higher than the others at $p<0.05$. Soil management system did not influence the rate of plant emergence. Final stands counted on 22 June 1992 averaged 90% of target plant populations. Superior stands were significantly higher than Atlantic (Figure 2.1); however, plant stands were not affected by pest or soil management systems.

Superior emerged more rapidly than Atlantic during 1993 (data not presented). Emergence of Superior was faster in the amended soil management system than the unamended system; however, emergence rate of Atlantic was not affected by soil management. Plant emergence at the late June ratings was slower for BIO than for the other pest management systems. This may have been due to plant burial from cultivation of the BIO system on 21 June 1993. For example, percent emergence on 24 June 1993 was 81%, 78%, and 72%, respectively, for the CONV, RI, and BIO systems (significantly different at $p<0.01$). Final crop stands averaged 92% of target stands during 1993 and were not affected by pest management system, variety, or soil management system (Figure 2.1).

During 1994, Atlantic in the amended plots had significantly lower emergence than it did in the unamended plots on 17 June (0% vs 33%, $p<0.01$) and 20 June (21% vs 68%, $p<0.01$). These differences were caused by delayed planting of the amended Atlantic plots due to wet weather. The amended plots were planted on 3 June 1994 compared to 27 May 1994 for the unamended plots. No soil management system effects were observed for Superior since planting of this variety was not delayed by rain. All Superior plots were planted between 27 and 31 May 1994. By 24 June 1994, the differences between the soil management systems were no longer present for Atlantic indicating that the late-planted plots had caught up with those planted earlier. Emergence of Superior lagged significantly behind Atlantic throughout the emergence period and was not significantly affected by pest management system during 1994. Final crop stands averaged 76% of target stands during 1994 and were significantly different between the varieties (Figure 2.1, 69% for Superior vs 83% for Atlantic, $p<0.01$). Final crop stands were not affected by pest or soil management system during 1994.

Leaf area and foliage vigor ratings

The 1991 growing season was much drier than is typical for Maine (Table 2.1), and crop growth was slow. Leaf area index (LAI) was estimated on 31 July 1991. Plants were much smaller than is typical for late July, and LAI measurements reflected this with an average of only 1.15. No significant effects of pest management system, soil management system, or variety were observed (data not presented). Based on visual ratings, the crop had reached only 74% ground cover by 8 August 1991. Typically, a healthy potato crop in Maine has achieved 95% to 100% ground cover at this time. No differences in foliage growth were observed between the pest management systems, soil management systems, or varieties (data not presented).

Rainfall was plentiful during the 1992 growing season (Table 2.1), and plant growth was vigorous in the CONV and RI systems. The BIO system did not receive any chemical fertilizer during 1992, and consequently the plants in this system were stunted and chlorotic during the entire growing season. Estimates of percent ground cover on 29 July 1992 revealed 84% and 89% ground cover for the CONV and RI systems, respectively, but only 50% ground cover in the BIO system. The BIO system had significantly lower percent ground cover than the other two systems ($p<0.01$). The amended system slightly improved crop ground cover on 29 July 1992 in the BIO system, but did not affect foliage growth in the CONV or the RI systems. On 29 July 1992 in the CONV and RI systems, the foliage in the amended system was noticeably lighter green than that in plots receiving the unamended system. LAI

Table 2.1 Monthly rainfall amounts at Aroostook Farm, Presque Isle, Maine, 1991–1994.

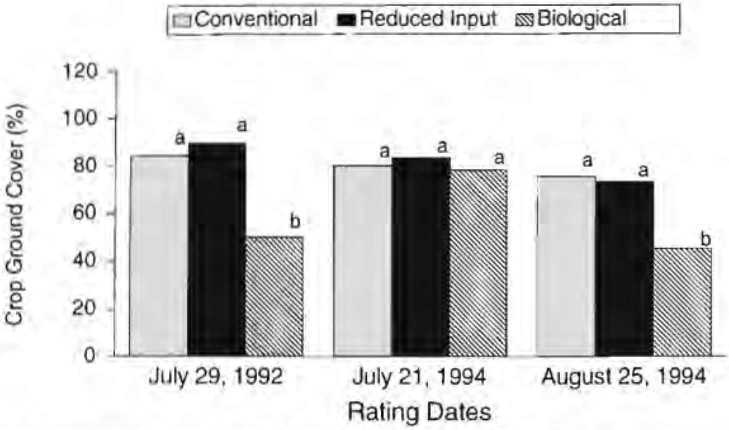
Month	Monthly Rainfall by Growing Season (in.) 1991	1992	1993	1994	30-year Average[1]
May	3.23	1.51	3.28	4.52	2.95
June	0.85	4.22	5.55	4.65	3.38
July	0.78	3.68	2.00	3.17	4.13
August	8.53	5.05	2.99	1.26	3.78
September	3.80	2.05	5.14	3.61	3.54
Totals					
June–Aug.	10.2	13.0	10.5	9.1	11.3
May–Sept.	17.2	16.5	19.0	17.2	17.8

[1] Based on data collected from 1951 to 1980.

values estimated on 5 August 1992 indicated that the leaf surface area present in the BIO system was significantly smaller than that present in the CONV and RI systems. LAI estimates were 2.65, 2.54, and 1.17, for the CONV, RI, and BIO systems, respectively.

Except for a three-week period in July, rainfall was plentiful during 1993 (Table 2.1). Consequently, plant growth was vigorous in all management systems. Estimates of percent ground cover on 5 August 1993 revealed an average ground cover of 95% and no significant differences between varieties or management systems (data not presented). Superior was noticeably lighter in foliage color than Atlantic; however, no differences in foliage vigor were noted between the management systems. By 25 August 1993, senescence had begun in the Superior variety. Foliage color was markedly lighter and percent ground cover was significantly lower than in Atlantic (77% vs 95%, $p<0.01$). Percent ground cover on 25 August 1993 was not significantly affected by the pest or soil management systems; however, late-season foliage of Atlantic was slightly darker in color and more vigorous in the amended system compared to the unamended system.

During 1994, initial differences in plant canopy growth were caused by delayed planting of several treatments. Conditions for plant growth after this initial period were excellent and foliage growth was vigorous in all pest management systems. On 6 July 1994, LAI of Superior lagged significantly behind that of Atlantic (1.48 vs 0.70, $p<0.01$). Leaf area of Superior was not affected by soil management systems, while that of Atlantic was significantly lower in the amended compared to the unamended soil management system. This early-season soil management effect was due to delayed planting of the amended Atlantic plots. There were no differences between the pest management systems. Estimates of percent crop ground cover on 21 July 1994 revealed an average ground cover of 92% for Atlantic and 62% for Superior (significantly different at $p<0.01$). This significant varietal difference reflected relatively poor stands (Figure 2.1) and seed vigor for Superior. There were no significant differences between the management systems on 21 July 1994 (Figure 2.2). Varietal differences in leaf area index persisted to the 18 August 1994 measurement date (Atlantic 3.99 vs Superior 3.47, $p<0.05$); however, no significant differences between pest or soil management systems were detected at this date. Percent ground cover ratings taken on 25 August 1994 revealed that the potato crop in the CONV and RI systems was significantly more vigorous with higher percent ground cover than in the BIO system (Figure 2.2). The amended



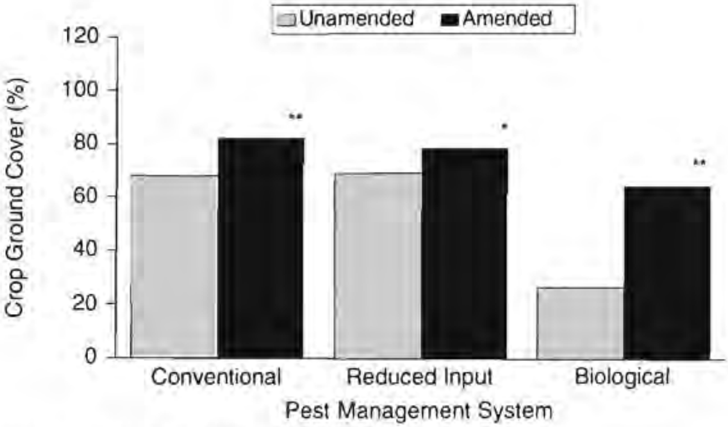
Biological pest management system received no fertilizer during 1992.
Within sample dates: means followed by the same letter are not significantly different.

Figure 2.2. Crop ground cover estimates, 1992 and 1994 (averaged over pest and soil management systems).

system had significantly higher percent ground cover (75% vs 54%, $p<0.01$), with plants that were darker green and more vigorous than those in the unamended system. Further analysis indicated that the amended system had a significant beneficial effect on crop ground cover within all three pest management systems; however, the beneficial effect was much more dramatic in the BIO system than the others (Figure 2.3). The differential effect of soil management across pest management systems suggests that the causal agent of the late-season defoliation was (1) suppressed in the amended soil management system, possibly because the amended system reduced crop nutrient and/or water stress; and/or (2) less sensitive to the BIO system's fungicidal materials than the synthetic fungicides used in the CONV and RI systems. The varieties did not differ in percent ground cover at this date; however, foliage of Atlantic was darker in color and more vigorous than Superior.

Total and U.S. #1 yields

Yields during 1991 were low due to relatively low rainfall (Tables 2.1 and 2.2; Figures 2.4 and 2.5). Total and U.S. #1 yields were significantly affected by pest management system and variety. Both were highest in the CONV system. Total yields in the CONV system exceeded those in the RI by 64 cwt/A except for disease control and vine desiccation. Yields in the RI system



Amended system receives a reduced rate of fertilizer.
Within pest management systems: * and ** indicate significant difference at p<0.05 and 0.01, respectively.

Figure 2.3. Crop ground cover estimates, 25 August 1994. Visual ratings (averaged over variety).

(primarily biological methods during 1991 except for disease control and vine desiccation) were slightly (25 cwt/A), but not significantly, higher than yields in the BIO system. Yield differences between the pest management systems during 1991 may have been due to varied pressure from insect pests, since weed control and disease pressure showed no striking visual differences between the management systems (data not presented). There were no significant differences in yield between the two soil management systems even though the amended system received only a half rate of at-planting chemical fertilizer (Figure 2.5, Table 2.2). Atlantic was significantly higher yielding than Superior during 1991 (Table 2.2). The yield difference between varieties was 28 cwt/A giving Atlantic a 16% yield advantage compared with Superior. Atlantic has a reputation for wide adaptation and greater stress resistance than Superior, so this yield difference was not unexpected during the dry 1991 growing season.

Rainfall was plentiful and well distributed during 1992 (Table 2.1), and yields were considerably higher than 1991 (Figures 2.4 and 2.5, Table 2.3). Total and U.S. #1 yields were significantly affected by pest management system. The CONV and the RI systems produced equal yields despite a dramatic reduction in pesticide use in the latter system. Crop growth in the BIO system

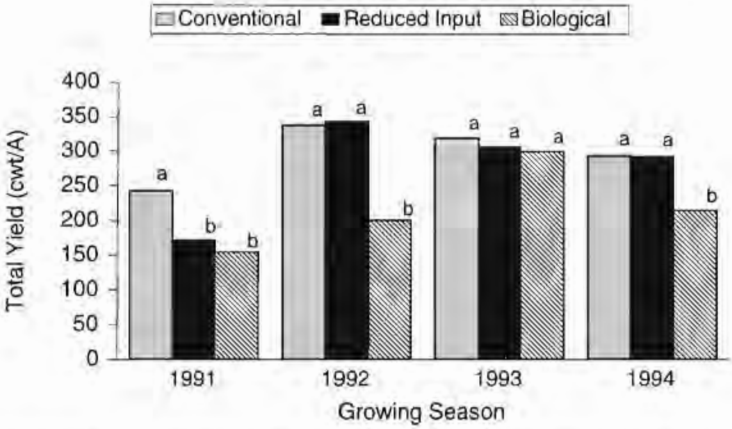
Table 2.2. Tuber yield and quality results for 1991.

Pest Mgt. System	Soil Mgt. System	Yield (cwt/A) Total	Yield (cwt/A) U.S.#1	Percent External Defects[1]	Tuber Size Distribution (%) <1⅞	1⅞ to 2¼"	2¼ to 4"	>4"	Specific Gravity
Atlantic									
CONV	-	284	268	0.6	5	24	71	0	1.088
CONV	+	240	226	1.2	5	27	69	0	1.093
RI	-	186	175	0.8	6	31	64	0	1.090
RI	+	208	196	0.4	6	28	67	0	1.091
BIO	-	141	127	0.5	9	43	48	0	1.091
BIO	+	183	168	0.5	8	40	52	0	1.093
Superior									
CONV	-	211	202	0.3	4	26	70	0	1.081
CONV	+	239	231	0.3	3	22	75	0	1.082
RI	-	157	145	0.6	7	37	56	0	1.082
RI	+	171	159	1.5	5	32	62	0	1.084
BIO	-	135	122	0.5	10	47	43	0	1.082
BIO	+	161	148	1.4	7	37	56	0	1.084
Main Effect Averages									
Pest Management									
CONV		244a	232a	0.6	4c	24c	71a	0	1.086
RI		180b	169b	0.8	6b	32b	62b	0	1.087
BIO		155b	141b	0.7	8a	42a	50c	0	1.087
Soil Management									
Unamended		186	173	0.5	7	34	59	0	1.086
Amended		200	188	0.9	6	31	63	0	1.088
Variety									
Atlantic		207	193	0.7	6	32	62	0	1.091
Superior		179	168	0.8	6	33	60	0	1.083
ANOVA Results									
Pest management		p<.01	p<.01	ns	p<.01	p<.01	p<.01	ns	ns
Soil management		ns	ns	p<.05	p<.05	ns	p<.10	p<.10	p<.01
Variety		p<.01	p<.01	ns	ns	ns	ns	ns	p<.01
Interactions		ns	ns	P*V P*S*V	ns	ns	ns	ns	ns

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

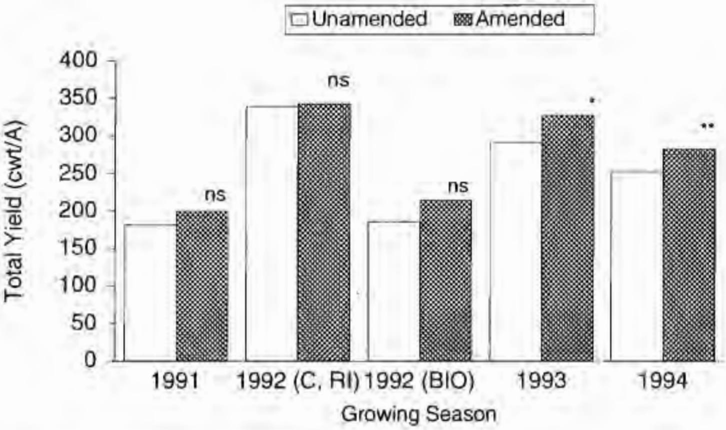
- = Unamended; + = Amended.

[1] Incidence of external defects was abnormally low during 1991. Those that were noted primarily represented poorly shaped tubers.



Biological pest management system received no insect control during 1991 and no fertilizer during 1992.
Within years: Means followed by the same letter are not significantly different.

Figure 2.4. Total yield by pest management system, 1991–1994 (averaged over soil management and variety).



Amended system receives a reduced rate of fertilizer.
Biological pest management system received no fertilizer during 1992.
Within years: * and ** indicate significant difference at $p<0.05$ and 0.01, respectively.

Figure 2.5. Total yield by soil management system, 1991–1994 (excluding 1992, averaged over pest management and variety).

Table 2.3. Tuber yield and quality results for 1992.

Pest Mgt. System	Soil Mgt. System	Yield (cwt/A)		Percent External Defects[1]	Tuber Size Distribution (%)				Specific Gravity
		Total	U.S.#1		<1⅞	1⅞ to 2¼"	2¼ to 4"	>4"	
Atlantic									
CONV	-	338	311	5.1	2	10	87	1	1.097
CONV	+	347	328	3.7	2	11	87	0	1.097
RI	-	341	316	5.1	2	11	86	0	1.094
RI	+	319	305	2.4	2	12	86	0	1.102
BIO	-/No Fert.	183	173	1.4	4	21	75	0	1.099
BIO	+/No Fert.	215	202	2.4	4	19	78	0	1.101
Superior									
CONV	-	328	308	3.3	3	14	83	0	1.081
CONV	+	338	324	1.0	3	15	82	0	1.085
RI	-	351	330	3.4	3	13	84	0	1.080
RI	+	366	347	2.1	3	18	79	0	1.085
BIO	-/No Fert.	190	175	1.2	7	33	61	0	1.090
BIO	+/No Fert.	212	200	1.4	5	25	71	0	1.095
Main Effect Averages									
Pest Management									
CONV		338a	318a	3.3a	2b	12b	85a	0	1.090b
RI		344a	324a	3.2a	3b	14b	84a	0	1.090b
BIO		200b	187b	1.6b	5a	24a	71b	0	1.097a
Soil Management									
Unamended		339	316	4.2	2	12	85	0	1.088
Amended		343	326	2.3	3	14	83	0	1.092
Unamended/ No Fertilizer		186	174	1.3	5	27	68	0	1.095
Amended/ No Fertilizer		214	201	1.9	4	22	74	0	1.098
Variety									
Atlantic		290	272	3.3	3	14	83	0	1.098
Superior		297	281	2.1	4	20	77	0	1.086
ANOVA Results									
Pest Management		p<.01	p<.01	p<.05	p<.01	p<.01	p<.01	ns	p<.01
Soil Mgt. within Pest Mgt.		ns	ns	p<.05	ns	p<.05	p<.05	ns	p<.05
Variety		ns	ns	p<.01	p<.01	p<.01	p<.01	ns	p<.01
Interactions		ns	ns	ns	ns	ns	ns	ns	P*V

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

- = Unamended; + = Amended.

[1] External defects during 1992 consisted primarily of misshapen and growth-cracked tubers.

was poor due to nutrient deficiency, and consequently yields were significantly lower than in the other systems. The yield in the BIO system was reduced by 138 cwt/A (41%) from the yield in the CONV system, primarily due to the complete omission of at-planting fertilizer in the BIO system. Application of the compost and manure did not adequately compensate for the omission of at-planting fertilizer during 1992 (Figure 2.5), probably because neither amendment was a good source of nitrogen during 1992 (see amendment nutrient analysis in Appendix Table A4). There were no significant differences in yields between the soil management systems or varieties during 1992 (Figure 2.5, Table 2.3).

Despite a three-week dry period in July (Table 2.1), rainfall was generally adequate during 1993 and yields were quite good (Figures 2.4 and 2.5, Table 2.4). Although the CONV system produced slightly higher yields than the other systems (+13 cwt/A vs RI and +20 cwt/A vs BIO), these differences were not significant, and there were no significant effects of pest management system on U.S. #1 yields. This lack of yield response occurred despite large differences in pest control practices and costs. The amended system produced significantly higher total yields (36 cwt/A, 12%) than the unamended system (Figure 2.5, Table 2.4), while using only 50% of the at-planting chemical fertilizer. U.S. #1 yields were not significantly different between the soil management systems. Atlantic produced significantly higher total (48 cwt/A, 17%) and U.S. #1 yields (28 cwt/A, 12%) than Superior during 1993 (Table 2.4).

Rainfall for August 1994 was considerably below the 30-year average, otherwise rainfall followed a relatively uniform and typical pattern (Table 2.1). Because of the dry August conditions, yields were considerably lower than those of 1993 (Figures 2.4 and 2.5, Table 2.5). The CONV and the RI systems were equal in yields and significantly higher yielding than the BIO system (+79 cwt/A, 27%). Low yields in the BIO system were probably related to the poor late-season ground cover previously noted in this system (Figures 2.2 and 2.3). The late-season foliage senescence observed in the BIO plots may have been due to a complex of crop stress and disease organisms favored by the low August rainfall and the BIO pest management practices (e.g., poorer aphid control than CONV and RI and/or a possible consequence of the extensive use of copper-based fungicides in BIO). Similarly, U.S. #1 yields were highest for CONV and RI with U.S. #1 yields significantly lower for BIO (76 cwt/A; Table 2.5). The amended system produced significantly higher total yields (29 cwt/A, 12%) and U.S. #1 yields (29 cwt/A, 12%) than the unamended system (Figure 2.5, Table 2.5), while nitrogen, phosphate, and potash fertilizer rates were reduced by

Table 2.4. Tuber yield and quality results for 1993.

Pest Mgt. System	Soil Mgt. System	Yield (cwt/A)		Percent External Defects[1]	Tuber Size Distribution (%)				Specific Gravity
		Total	U.S.#1		<1⅞	1⅞ to 2¼"	2¼ to 4"	>4"	
Atlantic									
CONV	-	328	263	15.9	3	21	74	1	1.091
CONV	+	346	276	15.9	3	18	77	2	1.089
RI	-	301	258	11.7	3	26	71	0	1.090
RI	+	369	281	21.8	3	17	81	0	1.091
BIO	-	309	264	11.2	4	25	71	0	1.089
BIO	+	344	282	14.1	3	16	79	1	1.090
Superior									
CONV	-	285	244	10.9	2	15	82	1	1.079
CONV	+	324	269	13.7	2	12	85	1	1.080
RI	-	273	237	10.0	2	12	84	1	1.082
RI	+	286	248	12.3	2	14	84	0	1.082
BIO	-	252	216	12.1	2	13	85	0	1.078
BIO	+	293	246	14.1	2	13	85	0	1.076
Main Effect Averages									
Pest Management									
CONV		320	263	14.1	3	17	80	1	1.085b
RI		307	256	13.9	2	17	80	0	1.086a
BIO		300	252	12.9	3	17	80	0	1.083c
Soil Management									
Unamended		291	247	12.0	3	19	78	1	1.085
Amended		327	267	15.3	3	15	82	1	1.085
Variety									
Atlantic		333	271	15.1	3	20	76	1	1.090
Superior		285	243	12.2	2	13	84	1	1.080
ANOVA Results									
Pest Management		p<.10	ns	ns	ns	ns	ns	ns	p<0.01
Soil Management		p<.05	ns	p<.05	ns	p<.05	p<.05	ns	ns
Variety		p<.01	p<.05	p<.05	p<.01	p<.01	p<.01	ns	p<0.01
Interactions		ns	ns	ns	ns	ns	ns	ns	ns

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.
- = Unamended; + = Amended.

[1] External defects during 1993 consisted primarily of misshapen tubers and those that were decaying (primarily those infected with late blight).

65%, 50%, and 70%, respectively. Atlantic produced significantly higher total (33 cwt/A, 13%) and U.S. #1 yields (30 cwt/A, 13%) than Superior during 1994 (Table 2.5).

Tuber size and external defects

The CONV system produced the largest tubers during 1991, while the BIO system had the smallest tuber size (Table 2.2). The

Table 2.5. Tuber yield and quality results for 1994.

Pest Mgt. System	Soil Mgt. System	Yield (cwt/A)		Percent External Defects[1]	Tuber Size Distribution (%)				Specific Gravity
		Total	U.S.#1		<1⅞	1⅞ to 2¼"	2¼ to 4"	>4"	
Atlantic									
CONV	-	291	271	2.9	4	25	71	0	1.100
CONV	+	307	284	3.2	4	24	72	0	1.103
RI	-	295	268	4.9	5	27	68	0	1.103
RI	+	320	296	3.8	4	22	74	0	1.103
BIO	-	209	188	2.0	9	48	43	0	1.104
BIO	+	284	259	2.7	6	31	63	0	1.101
Superior									
CONV	-	275	250	6.3	3	14	83	1	1.086
CONV	+	301	282	4.2	2	12	86	0	1.087
RI	-	280	263	4.0	3	17	80	0	1.088
RI	+	281	256	6.6	3	15	83	0	1.089
BIO	-	166	152	2.8	6	36	58	0	1.089
BIO	+	201	185	2.5	5	29	66	0	1.090
Main Effect Averages									
Pest Management									
CONV		294a	272a	4.1	3b	19b	78a	0	1.094
RI		294a	271a	4.8	3b	20b	76a	0	1.096
BIO		215b	196b	2.5	7a	36a	57b	0	1.096
Soil Management									
Unamended		253	232	3.8	5	28	67	0	1.095
Amended		282	261	3.8	4	22	74	0	1.095
Variety									
Atlantic		284	261	3.3	5	29	65	0	1.102
Superior		251	231	4.4	3	20	76	0	1.088
ANOVA Results									
Pest Management		p<.01	p<.01	ns	p<.01	p<.01	p<.01	ns	ns
Soil Management		p<.01	p<.01	ns	ns	p<.05	p<.05	ns	ns
Variety		p<.01	p<.01	ns	p<.01	p<.01	p<.01	ns	p<.01
Interactions		PxV	ns	ns	ns	ns	ns	ns	ns

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.
- = Unamended; + = Amended.

[1] External defects during 1994 consisted primarily of sunburned tubers.

RI system was intermediate. During 1992, tuber size in the BIO system was significantly smaller than in the other two pest management systems (Table 2.3). This size difference was primarily due to the absence of at-planting fertilizer application and subsequent poor growth of the crop. The pest management systems did not have an effect on tuber size during 1993 (Table 2.4); however, BIO again produced the smallest tuber size during 1994 (Table 2.5). Small tuber size during 1994 was probably due to early crop senescence in the BIO system during the dry month of August.

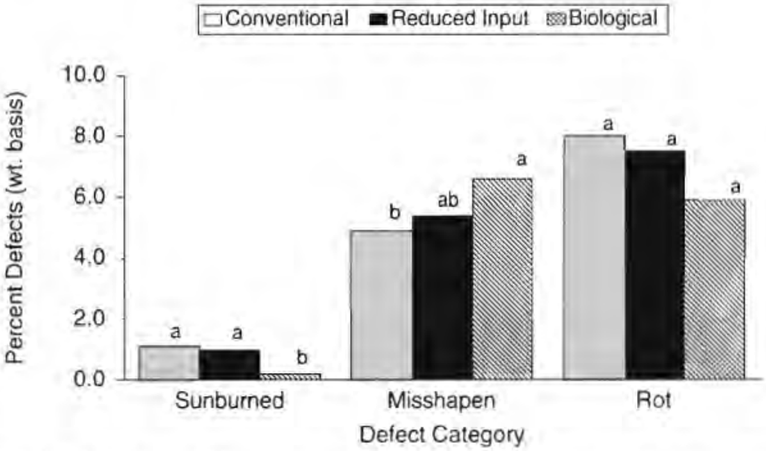
Soil management system did not affect tuber size during 1991 and had no significant effect in the plots that received at-planting chemical fertilizer during 1992 (Tables 2.2 and 2.3). Although the effect was quite small, the amended system significantly increased tuber size compared to the unamended system during 1993 (Table 2.4) and 1994 (Table 2.5). These results suggest that the drastic reduction in use of chemical fertilizer in the amended system has not compromised tuber size. The slightly larger tuber size observed for the amended system during 1993 and 1994 may indicate that this system reduced crop stress or increased nutrient availability, compared with the unamended system.

Varietal effects on tuber size were nonsignificant during 1991 (Table 2.2); however, Atlantic produced a significantly higher percentage of large-sized tubers than Superior during 1992 (Table 2.3). Superior had a significantly higher percentage of large-sized tubers than Atlantic during 1993 (Table 2.4) and 1994 (Table 2.5). These inconsistent varietal responses reflect genotype × environment interactions and are not unusual for the potato crop. Relatively large tuber size of Superior during 1994 was probably a consequence of poor plant stands, which increased the within-row plant spacing.

Incidence of tubers with external defects was very low during 1991, 1992, and 1994 (Tables 2.2, 2.3, and 2.5). The most dramatic system difference detected during these three years was a smaller incidence of defects (primarily misshapen tubers) in the 1992 BIO system (data not presented). This reduction probably had little to do with the pest management systems and more to do with the small tuber size caused by nutrient stress in the unfertilized BIO plots. Incidence of misshapen tubers decreases as tuber size decreases. Incidence of external tuber defects was much higher during 1993 than in the other years and was significantly higher in the amended soil management system than in the unamended system (Table 2.4). Incidence of defects was also significantly higher in Atlantic than in Superior. Tubers in the BIO system had less sunburn than tubers in the other pest management systems, but misshapen tubers were more prevalent in this system (Figure 2.6). More intensive cultivation for weed control may have improved soil coverage and reduced sunburn incidence. The effect on misshapen tubers cannot readily be explained. Incidence of tuber rot (primarily due to late blight) at harvest was not significantly influenced by pest management system (Figure 2.6), but was significantly higher in the amended system than in the unamended system (9.2% vs 5.1%, $p<0.01$). Percent misshapen tubers was significantly higher in Superior than Atlantic (7.4% vs 3.9%, $p<0.05$), while tuber rot was more prevalent in Atlantic than Superior (10.1% vs 4.2%, $p<0.01$). Varietal differences in the incidence of rot may be related to the degree of maturity at the time of drenching rains in September.

Specific gravity

Atlantic is a high specific gravity chipping variety, and as expected, it had a significantly higher specific gravity than Superior throughout the four years of the experiment (Tables 2.2 to 2.5). Specific gravity was slightly higher in the amended system than in the unamended system during 1991 (Table 2.2; 1.088 vs 1.086, $P<0.01$) and 1992 (Table 2.3; 1.092 vs 1.088, $p<0.05$, in the plots that received at-planting fertilizer). There was no effect of soil management system on specific gravity during 1993 (Table 2.4) and 1994 (Table 2.5). Because specific gravity declines with decreased plant maturity and increased nutrient availability, these data suggest that the reduced at-planting fertilizer applications in the amended system adequately compensated for the plant available nutrients added to this system in the manure and compost applications. Excess late-season nitrogen or potash release from the organic



Within a defect category: Means followed by the same letter are not significantly different ($p<0.05$).

Figure 2.6. Percent external defects by pest management system, 1993 (averaged over soil management and variety).

amendments would be expected to result in lower specific gravity in the amended plots compared with those receiving chemical fertilizer. The specific gravity increases observed in the amended system during 1991 and 1992 were possibly due to slight nitrogen deficiency (see plant vigor and nutrient analysis sections) and/or to partial use of the organic amendments as a potassium source for the potato crop. These organic amendments partially replaced muriate of potash (KCl) as the potato crop's potassium source. Compared to other fertilizer sources of potassium, KCl fertilizers can strongly depress specific gravity of potato tubers.

Pest management system had only minor effects on specific gravity, except during 1992 when specific gravity of the BIO system was significantly higher than the other pest management systems (Table 2.3). This effect was due to nutrient stress resulting from the omission of the at-planting fertilizer in the BIO system during 1992. The significant reduction in specific gravity in the BIO system during 1993 (Table 2.4) was probably not due to the pest management practices. This reduction would be expected because of nitrogen availability from the green manure rotation crop that preceded the 1993 BIO system potatoes. Green manure preceded 1993 potatoes only in the BIO system, while barley was the previous crop for potatoes grown in the CONV and RI systems. With rotation crops and soil management systems consistent across the pest management systems during 1994, pest management system did not affect specific gravity (Table 2.5).

Haulm and tuber dry matter production

Haulm biomass production just prior to vine destruction was determined as a quantitative measure of foliage vigor at season's end. Poor late-season vigor and low haulm biomass might occur for several reasons including poor foliar disease control, nutrient stress, drought stress, or insect damage. Conversely, a vigorous plant canopy just before vinekill is an indication that nutrient supply is in excess and that pests were effectively controlled. Haulm biomass production during 1991 was highest in the CONV system and lowest in the BIO plots (Table 2.6). These differences possibly reflected varying levels of insect pest control during the 1991 growing season. During 1992, potatoes in the BIO system did not receive chemical fertilizer and consequently exhibited nutrient stress through much of the season. Haulm biomass production was significantly lower for this pest management system than the others. Because of the good pest control achieved in all pest management systems during 1993, haulm biomass production was not significantly affected by pest management system; however, haulm biomass production was reduced in the BIO system during 1994 due to stress/pathogen-induced early senescence.

During each of the 1991 through 1993 growing seasons, haulm biomass production in the amended system was equal to that measured in the unamended system (Table 2.6). These results indicate that nutrient supply in the amended system was adequate despite a 35% reduction in use of nitrogen fertilizer and a 50% reduction in use of phosphate and potash. Haulm biomass production was significantly increased by the amended system relative to the unamended system during 1994. Haulm biomass production was significantly higher for Atlantic than Superior during all four growing seasons, reflecting the later vine maturity of Atlantic.

Percent tuber dry matter and final tuber yields were used to calculate dry biomass yield of tubers. Total dry biomass production was calculated as the sum of haulm and tuber dry biomass. Total and tuber dry biomass were significantly higher in the CONV system than in the other two pest management systems during 1991 (Table 2.6). Total and tuber biomass yields during 1992 were higher in the CONV and RI systems than in the BIO system. As noted above, this difference was probably due to nutrient stress rather than actual pest management practices. Total and tuber dry biomass yields were not affected by pest management system during 1993, but were reduced in the BIO system during 1994. The amended soil management system significantly increased total and tuber dry biomass yields during 1993 and 1994, but did not affect biomass production during 1991 or 1992. Total and tuber dry biomass yields for Atlantic were significantly greater than for Superior during 1991 through 1994.

Harvest index is calculated as the fraction of whole-plant dry biomass that is present as tubers. Harvest index for the 1991, 1992, 1993, and 1994 growing seasons averaged 0.73, 0.86, 0.78, and 0.76, respectively. It was not dramatically different between pest management systems, soil management systems, or varieties (Table 2.6). From this, it appears that the systems did not dramatically delay growth or affect maturity of the potato crop at harvest.

Leaf nutrient analysis and petiole nitrate content

Potato leaf and petiole samples were collected during each growing season to document the nutrient status of the crop. Leaf nutrient data from 1991 to 1993 were available for this report. Few effects of pest management system on leaf nutrient concentration were observed during 1991 (Table 2.7). Many effects of pest man-

Table 2.6. Dry matter yields within the potato plots.

		Potato Crop Pounds of Dry Matter per Acre			
Year	Management System or Variety	Haulms	Tubers	Total	Harvest Index
1991	Pest Management System				
	CONV	1641a	5041a	6682a	0.75
	RI	1351b	3687b	5038b	0.73
	BIO	1188b	3241b	4427b	0.73
	Soil Management System				
	Unamended	1381	3812	5193	0.73
	Amended	1406	4167	5573	0.75
	Variety				
	Atlantic	1585**	4450**	6035**	0.73
	Superior	1202	3529	4731	0.74
1992	Pest Management System				
	CONV	1221a	7498a	8718a	0.87b
	RI	975b	7645a	8620a	0.89a
	BIO	712c	4731b	5443b	0.87b
	Soil Management System				
	Unamended	1098	7393	8489	0.87
	Amended	1098	7750	8848	0.88
	No Fertilizer/Unamended	777	4333	5110	0.85
	No Fertilizer/Amended	647	5129	5775	0.89*
	Variety				
	Atlantic	1103**	6961**	8064**	0.86*
	Superior	836	6287	7123	0.88
1993	Pest Management System				
	CONV	1885	6792	8676	0.78
	RI	1796	6619	8415	0.78
	BIO	1903	6283	8186	0.77
	Soil Management System				
	Unamended	1825	6200*	8024*	0.77
	Amended	1898	6929	8827	0.78
	Variety				
	Atlantic	2119**	7404**	9523**	0.78
	Superior	1604	5725	7329	0.78
1994	Pest Management System				
	CONV	2244a	6770a	9013a	0.75
	RI	2212a	6930a	9142a	0.76
	BIO	1557b	5783b	6656b	0.76
	Soil Management System				
	Unamended	1874**	5900**	7774**	0.76
	Amended	2135	6631	8767	0.76
	Variety				
	Atlantic	2186**	7062**	9249**	0.76
	Superior	1823	5469	7292	0.75

Within a growing season: Pest management system means followed by the same letter are not significantly different. * and ** indicate significant soil management system or variety response at $p<0.05$ and $p<0.01$, respectively. CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

agement system were present during 1992, primarily because chemical fertilizer was omitted from the BIO system during 1992 (Table 2.8). Leaf and particularly petiole analysis indicated that nitrogen was very deficient in this management system (Table 2.8, Figure 2.7). Based on these analyses, the small size of the plants, and the pale green color, nitrogen was the limiting factor for the BIO system during 1992. Leaf concentrations of potassium, aluminum, boron, copper, and iron increased in the BIO system. The increase in leaf copper concentrations observed in the BIO system during 1992 (Table 2.8) was due to the use of copper-based fungicides in this system. Increases in the concentrations of the other nutrients in the BIO system that year may have been due to the restriction in growth caused by nitrogen deficiency. The BIO system had higher leaf nitrogen (Table 2.9) and petiole nitrate concentrations (mid-July 2.31% BIO vs 1.69% CONV and 1.77% RI, $p<0.01$) than the other two pest management systems during 1993 because a green manure rotation crop preceded potatoes in this system. This rotation crop was

Table 2.7. Leaf nutrient concentrations at flowering for 1991.

	Leaf Nutrient Concentration (%)					Leaf Nutrient Concentration (ppm)					
Treatment	N	Ca	K	Mg	P	Al	B	Cu	Fe	Mn	Zn
Main Effect Averages											
Pest Management											
CONV	5.32	1.25	5.53	0.77	0.36	134b	18.4	18.9	172.5b	303.3a	38.6a
RI	5.49	1.27	5.36	0.76	0.39	200a	19.9	20.2	234.6a	151.7b	27.1b
BIO	5.57	1.21	5.22	0.77	0.37	169ab	20.0	20.7	202.4ab	157.5b	25.4b
Soil Management											
Unamended	5.72	1.10	5.43	0.71	0.40	171	16.8	21.0	208.3	189.6	31.1
Amended	5.20	1.38	5.31	0.82	0.34	165	22.1	18.8	198.1	218.6	29.7
Variety											
Atlantic	5.43	1.27	5.21	0.78	0.36	174	21.1	20.0	215.1	218.3	31.0
Superior	5.49	1.22	5.53	0.75	0.38	161	17.8	19.8	191.3	189.9	29.7
ANOVA Results											
Pest Management	ns	ns	ns	ns	ns	p<.05	ns	ns	p<.05	p<.01	p<.01
Soil Management	p<.01	p<.01	ns	p<.01	p<.01	ns	p<.01	p<.01	ns	p<.05	ns
Variety	ns	ns	ns	ns	p<.05	ns	p<.01	ns	p<.05	p<.05	ns
Interactions	ns	ns	ns	ns	ns	ns	V*S	ns	P*V	ns	ns

N = nitrogen, Ca = calcium, K = potassium, Mg = magnesium, P = phosphorus, Al = aluminum, B = boron, Cu = copper, Fe = iron, Mn = manganese, Zn = zinc.
CONV= conventional, RI = reduced input, and BIO = biological pest management systems.

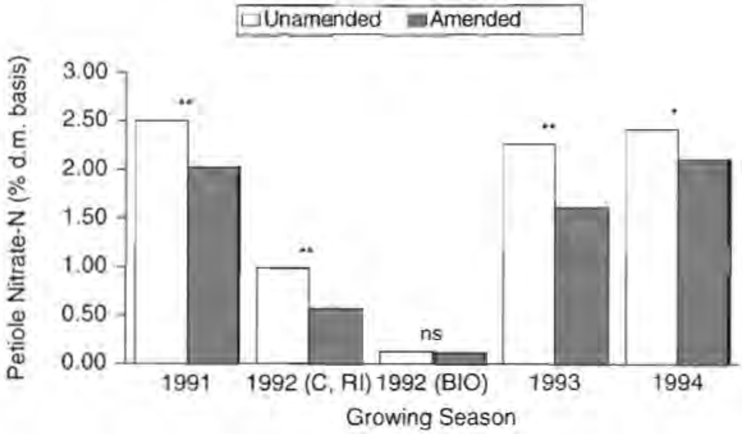
introduced into the experiment to enhance nitrogen fertility levels. Beginning in 1994, this green manure rotation crop preceded potatoes in the amended plots within all three pest managements systems (Appendix Table A3). The CONV system had higher leaf manganese and zinc concentrations than the other management systems during 1991 and 1992. These nutrients were probably present at higher levels due to the intensive use of fungicides containing manganese and zinc within this system. Surprisingly, this increase was not noted during 1993. The increase in leaf copper concentrations observed in the BIO system during 1992 was again present during 1993 (Table 2.9), presumably due to the use of copper-based fungicides.

The amended soil management system increased foliar concentrations of calcium, magnesium, manganese, and boron when com-

Table 2.8. Leaf nutrient concentrations at flowering for 1992.

	Leaf Nutrient Concentration (%)					Leaf Nutrient Concentration (ppm)					
Treatment	N	Ca	K	Mg	P	Al	B	Cu	Fe	Mn	Zn
Main Effect Averages											
Pest Management											
CONV	4.96b	1.28	3.62b	0.94a	0.293	146b	17.3b	15.5b	143.5b	367.9a	36.0a
RI	5.16a	1.36	3.62b	0.96a	0.300	106b	18.1b	18.4b	149.6b	127.5b	16.1b
BIO	4.39c	1.47	4.34a	0.79b	0.302	268a	24.0a	164.4a	267.4a	117.9b	17.4b
Soil Management											
Unamended	5.22	1.26	3.41	1.04	0.298	122	15.6	17.1	144.1	253.1	26.1
Amended	4.90	1.38	3.83	0.86	0.294	31	19.8	16.8	149.0	242.3	26.0
Amended/ No Fert.	4.39	1.43	4.40	0.72	0.312	218	24.9	154.5	225.9	126.5	17.8
Unamended/ No Fert.	4.38	1.50	4.28	0.85	0.291	319	23.1	174.2	308.9	109.3	17.1
Variety											
Atlantic	5.07	1.45	3.72	0.99	0.311	159	21.0	63.1	179.6	217.6	23.9
Superior	4.60	1.29	4.00	0.80	0.286	188	18.6	69.1	194.0	191.3	22.5
ANOVA Results											
Pest Management	p<.01	p<.10	p<.01	p<.05	ns	p<.01	p<.01	p<.01	p<.01	p<.01	p<.01
Soil Mgt. within Pest Management	p<.01	p<.05	p<.01	p<.01	ns	p<.01	p<.01	ns	p<.01	ns	ns
Variety	p<.01	p<.01	p<.01	p<.01	p<.01	p<.05	p<.01	ns	ns	p<.01	p<.05
Interactions	ns	ns	ns	ns	ns	P*V	ns	ns	P*V	V*S(P)	P*V V*S(P)

N = nitrogen, Ca = calcium, K = potassium, Mg = magnesium, P = phosphorus, Al = aluminum, B = boron, Cu = copper, Fe = iron, Mn = manganese, Zn = zinc.
CONV = conventional, RI = reduced input, and BIO = biological pest management systems.



Amended system receives a reduced rate of fertilizer.
Biological pest management system received no fertilizer during 1992.
Within sample dates: * and ** indicate significant difference at $p<0.05$ and $p<0.01$, respectively.

Figure 2.7. Petiole nitrate-nitrogen by soil management system, 1991–1994 (excluding 1992, averaged over pest management system and variety). Mid-July sampling, except late July for 1992.

pared to the unamended system during 1991 (Table 2.7). The amended system decreased leaf nitrogen, petiole nitrate-nitrogen, phosphorus, and copper levels relative to the unamended system (Table 2.7, Figure 2.7). This suggests that the amendments were providing less of these nutrients than was expected based on their nutrient composition. Petiole nitrate concentrations were sufficiently low as to indicate that nitrogen was deficient in the amended system and that nitrogen would probably have limited yields in the amended system if drought had not reduced overall yield potential during 1991. Similarly, petiole and leaf analysis during 1992 and 1993 indicated that nitrogen status of the amended system was significantly lower than that of the unamended system and that the plant nitrogen status was below optimum (Tables 2.8 and 2.9; Figure 2.7). Petiole analysis conducted during the 1994 growing season indicated that nitrogen status had improved greatly in the amended system due to the introduction of the green manure crop (Figure 2.7). Petiole nitrate-nitrogen concentrations were within the optimum range despite a 65% reduction in nitrogen fertilizer use. Although petiole nitrate-nitrogen levels were within

Table 2.9. Leaf nutrient concentrations at flowering for 1993.

	Leaf Nutrient Concentration (%)					Leaf Nutrient Concentration (ppm)					
Treatment	N	Ca	K	Mg	P	Al	B	Cu	Fe	Mn	Zn
Main Effect Averages											
Pest Management											
CONV	5.07b	1.21	4.04	0.82	0.353	30.5	20.0	22.2b	134.3	150.6	22.8
RI	5.02b	1.28	4.00	0.83	0.357	40.9	20.2	20.6b	132.0	136.8	19.3
BIO	5.47a	1.22	4.15	0.86	0.364	43.6	20.3	84.1a	123.9	144.1	22.2
Soil Management											
Unamended	5.37	1.14	4.05	0.85	0.358	39.4	16.6	42.9	130.6	174.5	21.6
Amended	5.00	1.33	4.09	0.83	0.358	37.3	23.8	41.7	129.6	113.1	21.2
Variety											
Atlantic	5.19	1.24	3.63	0.84	0.350	32.3	17.6	39.8	136.6	146.1	20.1
Superior	5.19	1.23	4.50	0.84	0.366	44.4	22.8	44.8	123.6	141.6	22.8
ANOVA Results											
Pest Management	p<.01	ns	ns	ns	ns	p<.10	ns	p<.01	ns	ns	p<.10
Soil Management	p<.01	p<.01	ns	ns	ns	ns	p<.01	ns	ns	p<.01	ns
Variety	ns	ns	p<.01	ns	p<.01	p<.01	p<.01	p<.01	ns	ns	p<.05
Interactions	P*V	ns	ns	P*S	V*S	ns	ns	P*V	ns	P*S	ns

N = nitrogen, Ca = calcium, K = potassium, Mg = magnesium, P = phosphorus, Al = aluminum, B = boron, Cu = copper, Fe = iron, Mn = manganese, Zn = zinc.
CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

the optimum range they were significantly lower than those obtained in the heavily fertilized, unamended system. The amended system had increased leaf concentrations of calcium and boron during both 1992 and 1993 (Table 2.8 and 2.9). Leaf potassium concentration was increased during 1992, while magnesium concentrations decreased. Based on the leaf analysis, phosphorus concentrations were not affected by the amended systems and remained within acceptable ranges during all three years.

Atlantic often had significantly higher leaf nutrient concentrations than Superior during the 1991 and 1992 seasons of this study (Tables 2.7 and 2.8). For example, Atlantic had significantly higher leaf boron, iron, and manganese concentrations than Superior during 1991 (Table 2.7). Exceptions were that 1991 leaf phosphorus concentration and mid-July petiole nitrate-nitrogen concentration of Superior (2.39% vs 2.18, p<0.01) were higher than Atlantic. Also, potassium and aluminum concentrations were significantly lower for Atlantic than Superior during 1992 (Table 2.8). Copper and iron concentrations did not differ between the two varieties during 1992. Leaf concentrations of potassium, phosphorus, aluminum, boron, copper, and zinc during 1993 were significantly higher for Superior than Atlantic (Table 2.9). Petiole nitrate-nitrogen concentrations during July were also higher for Superior than Atlantic (2.07% vs 1.78, $p<0.05$).

Nutrient analysis and uptake

Nutrient concentrations of potato plant and tuber samples were determined from samples collected just before harvest. These concentrations along with biomass yields were used to calculate nutrient uptake and removal by the potato crop. Only data from 1991 to 1993 were available for this report. Uptake and removal of macro- and secondary nutrients were strongly associated with high-yielding systems during each growing season. For example, the CONV system was the highest yielding pest management system during 1991, and this system had the highest uptake and removal of all macro- and secondary nutrients (Table 2.10). Crop removal of boron, copper, and manganese was also enhanced in this system (Table 2.11). During 1992, the two high-yielding pest management systems, CONV and RI, had significantly higher uptake and removal of essentially all nutrients when compared to the nitrogen-stressed BIO system (Table 2.12 and 2.13). During 1993, all three pest management systems produced high yields, and consequently few differences in nutrient uptake and crop removal were detected between the pest management systems (Tables 2.14 and 2.15).

Atlantic, being later maturing and generally higher yielding than Superior, had significantly higher uptake and removal of most macro- and secondary nutrients during all three growing seasons (Tables 2.10 to 2.15). Micronutrient differences between varieties were less consistent.

Despite drastic reductions in the use of chemical fertilizer in the amended system, nutrient uptake kept pace with the chemically fertilized, unamended treatment in most cases. Uptake of nitrogen, phosphorus, potassium and most other nutrients was equal to the unamended system during 1991 (Tables 2.10 and 2.11) and 1992 (Tables 2.12 and 2.13). Total uptake and removal of phosphorus, potassium, and boron were significantly higher in the amended system when compared to the unamended system during 1993 (Tables 2.14 and 2.15). Total uptake of calcium increased significantly in the amended system during 1991 (Table 2.10) and 1993 (Table 2.14). These results, when combined with the favorable

Table 2.10. Uptake and removal of major and secondary nutrients by the 1991 potato crop.

		Nutrient Uptake by the Potato Crop (lbs/A)[1]									
Pest Mgt.	Soil Mgt.	N		P		K		Ca		Mg	
System	System	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.
Atlantic											
CONV	-	132.1	70.7	14.7	10.4	204.6	113.0	43.1	1.09	39.3	5.8
CONV	+	111.0	57.8	12.6	8.8	166.6	95.2	41.5	0.97	34.6	4.9
RI	-	81.8	46.7	10.2	7.6	131.5	76.7	25.8	0.87	21.7	4.3
RI	+	93.7	51.3	10.7	7.8	149.0	88.6	32.6	0.83	27.6	4.7
BIO	-	72.1	43.3	8.9	6.3	107.2	62.2	17.9	0.60	19.0	3.5
BIO	+	83.4	50.3	9.8	7.0	137.8	82.5	25.6	0.70	25.3	4.5
Superior											
CONV	-	88.5	54.7	10.8	8.1	136.9	76.0	27.1	0.98	24.1	5.0
CONV	+	87.4	54.8	10.2	7.9	142.2	81.5	29.4	1.03	22.3	5.2
RI	-	73.4	45.9	9.4	6.9	105.8	60.3	21.2	0.88	19.9	4.2
RI	+	79.0	50.0	9.6	7.4	115.8	72.8	25.5	0.95	19.8	4.7
BIO	-	62.0	42.8	8.3	6.4	91.4	55.5	13.9	0.62	15.8	3.7
BIO	+	64.9	40.9	8.1	5.9	105.9	61.7	21.5	0.64	20.3	4.0
Main Effect Averages											
Pest Management											
CONV		104.8a	59.5a	12.1a	8.8a	162.6a	91.4a	35.2a	1.02a	30.1a	5.2a
RI		82.0b	48.5b	10.0b	7.4b	125.5b	74.6b	26.3b	0.88a	22.3b	4.5ab
BIO		70.6c	44.3b	8.8b	6.4c	110.6c	65.5b	19.7c	0.64b	20.1b	3.9 b
Soil Management											
Unamended		85.0	50.7	10.4	7.6	129.6	74.0	24.8	0.84	23.3	4.4
Amended		86.6	50.9	10.2	7.5	136.2	80.4	29.4	0.85	25.0	4.7
Variety											
Atlantic		95.7	53.4	11.1	8.0	149.5	86.4	31.1	0.84	27.9	4.6
Superior		75.9	48.2	9.4	7.1	116.3	68.0	23.1	0.85	20.4	4.5
ANOVA Results											
Pest Management		p<.01	p<.01	p<.01	p<.01	p<.01	p<.01	p<.01	p<.01	p<.01	p<.05
Soil Management		ns	ns	ns	ns	ns	ns	p<.01	ns	ns	ns
Variety		p<.01	ns	p<.01	p<.05	p<.01	p<.01	p<.01	ns	p<.01	ns
Interactions		ns	ns	ns	ns	PxS	ns	PxV	ns	PxV PxS	ns

N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium; and Tot. = total, Tub. = tubers.
CONV = conventional, RI = reduced input, and BIO = biological pest management systems.
- = Unamended; + = Amended.
[1]Based on analysis of haulm and tuber samples collected just prior to vine destruction.

leaf analysis and yield data presented above, indicate that the compost and the manure used in the amended system have effectively replaced 50% of the phosphate and potash fertilizers used on a potato crop while maintaining nutrient uptake. Nearly 40% reductions in nitrogen fertilization rates were achieved during the first three years of this study; however, nitrogen fertility status in the amended system was slightly lower than that in the unamended system from 1991 to 1993. Incorporation of the legume green manure crop into the amended system during 1994 appeared to correct this nitrogen management problem. During 1994, petiole nitrate levels were maintained at adequate levels through mid-season in the amended system (Figure 2.7) while use of synthetic nitrogen fertilizer was reduced by 65%.

Relationship of tuber yield with crop nutrient management

Petiole nitrate concentrations were not significantly correlated with yields during 1991, suggesting that nitrogen availability was not a major yield-limiting factor during 1991. This was expected since drought and insect pest pressure were perceived to be the limiting factors during the initial year of study.

Data collected during 1992 indicate that tuber yields were closely related to the size of the potato crop canopy. Linear regression showed that yields were significantly related to LAI and visual ratings of percent ground cover by the crop (r^2=0.80 and 0.91, respectively, $p<0.01$). Yield differences during 1992 were primarily caused by nitrogen deficiency in the BIO system, which received no chemical fertilizer. Average LAI was significantly reduced in this management system. Leaf nitrogen concentrations during July 1992 were positively correlated with tuber yields ($p<0.01$, $r=0.59$). This again indicates that nitrogen fertility was an important yield determinant, at least when comparing the fertilized plots with those not receiving any chemical fertilizer. Leaf manganese ($p<.01$, $r=0.40$), zinc ($p<0.05$, $r=0.35$), and magnesium ($p<0.01$, $r=0.37$) concentrations at flowering were also positively correlated with yields. This was probably due to the association of the former two nutrients as components of fungicides within the two pest management systems (CONV and RI) that received at-planting chemical fertilizers. Most other nutrients were negatively correlated with tuber yield during 1992.

From leaf samples collected at flowering during 1993, only calcium concentrations displayed a significant correlation with yield ($p<.05$, $r=0.36$). Petiole nitrate-nitrogen concentrations and leaf potassium and phosphorus concentrations were negatively correlated with yields during 1993. These data indicate that factors other than macronutrient availability were the primary yield determinants during 1993. Leaf analysis data for 1994 were not available at the time of this writing.

Table 2.11. Uptake and removal of minor nutrients by the 1991 potato crop.

Pest Mgt. System	Soil Mgt. System	Nutrient Uptake by the Potato Crop (lbs/A)[1]											
		Al		B		Cu		Fe		Mn		Zn	
		Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers
Atlantic													
CONV	Unamended	0.2	0.6	0.104	0.032	0.075	0.038	10.6	0.653	1.54	0.045	0.237	0.079
CONV	Amended	7.6	0.5	0.086	0.027	0.063	0.032	7.9	0.541	1.11	0.037	0.180	0.065
RI	Unamended	11.1	0.5	0.080	0.022	0.060	0.027	11.0	0.590	0.79	0.037	0.153	0.059
RI	Amended	9.5	0.4	0.088	0.025	0.063	0.030	9.4	0.447	0.82	0.035	0.177	0.078
BIO	Unamended	13.1	0.4	0.075	0.017	0.052	0.024	11.4	0.456	0.72	0.030	0.133	0.045
BIO	Amended	13.2	0.4	0.090	0.024	0.060	0.029	12.3	0.451	0.86	0.032	0.154	0.055
Superior													
CONV	Unamended	11.1	0.6	0.074	0.024	0.062	0.032	11.1	0.638	0.90	0.043	0.171	0.077
CONV	Amended	8.9	0.7	0.072	0.025	0.059	0.033	8.6	0.745	0.91	0.045	0.171	0.076
RI	Unamended	14.5	0.4	0.080	0.019	0.058	0.028	12.7	0.508	0.78	0.038	0.157	0.064
RI	Amended	9.8	0.5	0.070	0.022	0.055	0.030	9.6	0.602	0.70	0.040	0.144	0.068
BIO	Unamended	13.4	0.4	0.069	0.018	0.050	0.026	10.4	0.444	0.52	0.032	0.129	0.057
BIO	Amended	12.9	0.4	0.077	0.018	0.055	0.026	12.2	0.448	0.62	0.033	0.145	0.058
Main Effect Averages													
Pest Management													
CONV		9.5	0.6	0.084	0.027a	0.065	0.034a	9.5	0.644	1.12a	0.043a	0.190a	0.074
RI		11.2	0.5	0.080	0.022b	0.059	0.029b	10.7	0.536	0.77b	0.038ab	0.158b	0.067
BIO		13.2	0.4	0.078	0.019b	0.054	0.026b	11.6	0.450	0.68b	0.032b	0.140b	0.054
Soil Management													
Unamended		12.2	0.5	0.080	0.022	0.059	0.029	11.2	0.548	0.88	0.038	0.163	0.063
Amended		10.3	0.5	0.081	0.024	0.059	0.030	10.0	0.539	0.84	0.037	0.162	0.066

Table 2.11. Continued.

Pest Mgt. System	Soil Mgt. System	Nutrient Uptake by the Potato Crop (lbs/A)[1] Al Tot.	Al Tubers	B Tot.	B Tubers	Cu Tot.	Cu Tubers	Fe Tot.	Fe Tubers	Mn Tot.	Mn Tubers	Zn Tot.	Zn Tubers
Variety													
Atlantic		10.8	0.5	0.087	0.024	0.062	0.030	10.4	0.523	0.97	0.036	0.172	0.064
Superior		11.8	0.5	0.074	0.021	0.056	0.029	10.8	0.564	0.74	0.039	0.153	0.066
ANOVA Results													
Pest Management		ns	ns	ns	p<.05	ns	p<.05	ns	ns	p<.01	p<.05	p<.05	ns
Soil Management		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Variety		ns	ns	p<.01	p<.05	p<.05	ns	ns	ns	p<.01	ns	p<.05	ns
Interactions		ns	ns	ns	ns	ns	ns	PxS	ns	PxV PxS PxVxS	ns	ns	ns

Al = aluminun, B = boron, Cu = copper, Fe = iron, Mn = manganese, Zn = zinc.

[1] Based on analysis of haulm and tuber samples collected just prior to vine destruction.

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

Table 2.12. Uptake and removal of major and secondary nutrients by the 1992 potato crop.

		Nutrient Uptake by the Potato Crop (lbs/A)[1]									
Pest Mgt.	Soil Mgt.	N		P		K		Ca		Mg	
System	System	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.
Atlantic											
CONV	-	98.1	58.7	14.5	12.0	162.6	114.4	20.9	0.82	29.7	5.0
CONV	+	94.3	59.8	14.2	11.8	160.9	115.7	23.7	0.66	25.5	5.5
RI	-	91.2	59.2	14.4	12.1	139.5	105.9	20.1	0.74	28.4	4.9
RI	+	73.4	46.2	12.6	10.6	150.1	105.6	22.7	0.62	22.5	4.9
BIO	-/No Fert.	55.6	33.5	8.3	6.8	89.6	63.2	14.6	0.42	15.7	3.5
BIO	+/No Fert.	44.9	30.2	9.3	8.1	100.1	74.2	11.8	0.72	10.7	4.0
Superior											
CONV	-	73.8	54.0	11.4	9.9	119.1	88.1	17.6	0.72	22.2	4.9
CONV	+	72.0	55.1	11.7	10.3	128.3	97.9	18.0	0.61	19.6	5.6
RI	-	84.3	72.8	12.3	11.3	121.4	102.2	11.4	0.84	17.9	6.3
RI	+	87.4	75.0	13.2	12.1	134.9	108.6	16.3	0.89	18.5	7.2
BIO	-/No Fert.	55.2	39.7	8.5	7.3	90.0	63.6	15.3	0.46	15.3	4.6
BIO	+/No Fert.	43.4	31.7	9.3	8.3	95.7	74.3	12.6	0.61	10.3	4.6
Main Effect Averages											
Pest Management											
CONV		84.6a	56.9a	12.9a	11.0a	142.7a	104.0a	20.1a	0.70	24.2a	5.3a
RI		84.1a	63.3a	13.1a	11.5a	136.5a	105.6a	17.6ab	0.77	21.8a	5.8a
BIO		50.1b	34.0b	8.8b	7.6b	93.4b	68.5b	13.7b	0.54	13.1b	4.2b
Soil Management											
Unamended		86.9	61.2	13.1	11.3	135.6	102.6	17.5	0.78	24.5	5.3
Amended		81.8	59.0	12.9	11.2	143.5	107.0	20.2	0.69	21.5	5.8
Unamended/ No Fertilizer		44.0	31.1	9.3	8.2	97.6	74.3	12.3	0.66	10.5	4.3
Amended/ No Fertilizer		55.4	36.6	8.4	7.0	89.8	63.4	14.9	0.44	15.5	4.1
Variety											
Atlantic		77.6	48.7	12.3	10.3	135.2	97.5	19.3	0.66	22.6	4.7
Superior		69.4	54.7	11.1	9.9	114.9	89.1	15.2	0.69	17.3	5.5
ANOVA Results											
Pest Management		p<.01	p<.01	p<.01	p<.01	p<.01	p<.01	p<.05	ns	p<.01	p<.01
Soil Mgt. within Pest Mgt.		ns	ns	ns	ns	ns	ns	ns	ns	p<.05	ns
Variety		p<.1	p<.05	p<.05	ns	p<.01	ns	p<.01	ns	p<.01	p<.01
Interactions		P*V	P*V	ns	ns	ns	P*V	P*V	ns	P*V	P*V

N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium; and Tot. = total, Tub. = tubers.

CONV = conventional RI = reduced input, and BIO = biological pest management systems.

- = Unamended; + = Amended.

[1] Based on analysis of haulm and tuber samples collected just prior to vine destruction.

Table 2.13. Uptake and removal of minor nutrients by the 1992 potato crop.

Pest Mgt. System	Soil Mgt. System	Nutrient Uptake by the Potato Crop (lbs/A)[1]											
		Al		B		Cu		Fe		Mn		Zn	
		Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers
Atlantic													
CONV	Unamended	5.5	0.7	0.055	0.023	0.144	0.040	5.5	0.772	0.81	0.049	0.178	0.088
CONV	Amended	5.9	0.7	0.059	0.026	0.126	0.039	6.0	0.828	0.68	0.047	0.153	0.069
RI	Unamended	4.9	0.6	0.049	0.021	0.072	0.044	4.9	0.761	0.51	0.046	0.143	0.087
RI	Amended	5.1	0.6	0.053	0.023	0.056	0.032	4.8	0.682	0.40	0.039	0.121	0.069
BIO	Unamended/No Fert.	4.6	0.4	0.037	0.017	0.226	0.022	4.3	0.504	0.20	0.027	0.069	0.040
BIO	Amended/No Fert.	2.6	0.4	0.034	0.018	0.196	0.031	2.4	0.446	0.17	0.032	0.071	0.043
Superior													
CONV	Unamended	7.5	0.7	0.048	0.019	0.117	0.033	7.1	0.874	0.66	0.048	0.162	0.085
CONV	Amended	8.2	0.7	0.054	0.022	0.120	0.036	7.9	0.795	0.63	0.045	0.168	0.077
RI	Unamended	6.3	0.8	0.047	0.025	0.064	0.039	6.2	0.913	0.30	0.056	0.153	0.103
RI	Amended	6.0	0.7	0.054	0.028	0.062	0.038	5.8	0.838	0.34	0.056	0.142	0.092
BIO	Unamended/No Fert.	4.0	0.5	0.038	0.019	0.212	0.025	3.8	0.619	0.19	0.034	0.100	0.057
BIO	Amended/No Fert.	6.0	0.5	0.042	0.019	0.275	0.027	5.4	0.591	0.20	0.033	0.080	0.045
Main Effect Averages													
Pest Management													
CONV		6.8a	0.7a	0.054a	0.022a	0.127b	0.037a	6.6a	0.817a	0.69a	0.047a	0.165a	0.080a
RI		5.6ab	0.7a	0.051a	0.024a	0.064c	0.038a	5.4ab	0.798a	0.39b	0.049a	0.140a	0.088a
BIO		4.4b	0.5b	0.038b	0.018b	0.229a	0.026b	4.1b	0.546b	0.19c	0.031b	0.081b	0.046b

Table 2.13. Continued.

		Nutrient Uptake by the Potato Crop (lbs/A)[1]											
Pest Mgt. System	Soil Mgt. System	Al		B		Cu		Fe		Mn		Zn	
		Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers
Soil Management													
Unamended		6.1	0.7	0.050	0.022	0.100	0.039	5.9	0.830	0.57	0.050	0.159	0.091
Amended		6.3	0.7	0.055	0.025	0.091	0.036	6.1	0.786	0.51	0.047	0.146	0.077
Unamended/No Fertilizer		4.3	0.5	0.038	0.018	0.219	0.023	4.1	0.562	0.19	0.030	0.084	0.049
Amended/No Fertilizer		4.5	0.5	0.038	0.019	0.241	0.029	4.1	0.528	0.19	0.033	0.076	0.044
Variety													
Atlantic		4.9	0.6	0.048	0.021	0.134	0.035	4.8	0.675	0.47	0.040	0.125	0.067
Superior		6.3	0.7	0.047	0.022	0.142	0.033	6.0	0.772	0.39	0.045	0.134	0.077
ANOVA Results													
Pest Management		p<.05	p<.05	p<.05	p<.05	p<.01	p<.01	p<.05	p<.05	p<.01	p<.05	p<.01	p<.01
Soil Mgt. within Pest Mgt.		ns	ns	ns	ns	ns	p<.05	ns	ns	ns	ns	ns	ns
Variety		p<.01	ns	ns	ns	ns	ns	p<.01	ns	p<.05	ns	ns	ns
Interactions		ns	ns	ns	P*V	V*S(P)	ns	ns	ns	ns	ns	ns	ns

Al = aluminun, B = boron, Cu = copper, Fe = iron, Mn = manganese, Zn = zinc.

[1] Based on analysis of haulm and tuber samples collected just prior to vine destruction.

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

Table 2.14. Uptake and removal of major and secondary nutrients by the 1993 potato crop.

		Nutrient Uptake by the Potato Crop (lbs/A)[1]									
Pest Mgt.	Soil Mgt.	N		P		K		Ca		Mg	
System	System	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.	Tot.	Tub.
Atlantic											
CONV	-	157.8	115.1	16.3	13.1	195.3	131.0	27.3	1.22	38.2	7.8
CONV	+	143.3	104.2	18.1	14.7	205.9	139.6	36.7	1.09	36.9	8.4
RI	-	149.4	104.9	15.6	12.4	186.5	123.1	35.7	1.20	42.7	7.4
RI	+	147.1	111.0	18.6	15.5	214.3	144.1	30.7	1.28	35.1	9.1
BIO	-	167.8	113.3	15.1	11.7	214.7	131.6	34.8	1.18	44.5	7.8
BIO	+	165.7	114.7	16.9	13.6	228.3	144.0	42.0	1.76	46.7	11.7
Superior											
CONV	-	136.7	105.3	13.4	11.1	155.4	103.9	27.2	1.20	34.2	7.0
CONV	+	131.0	104.4	14.7	12.6	181.8	121.6	28.9	1.01	26.7	8.2
RI	-	130.9	103.1	13.6	11.3	144.1	103.9	25.8	1.18	29.9	7.4
RI	+	119.7	94.2	14.4	12.2	167.0	111.1	33.1	0.96	26.5	7.6
BIO	-	130.2	96.2	11.3	9.2	155.6	99.9	26.6	1.10	29.8	6.6
BIO	+	140.4	103.1	13.7	11.1	164.3	109.0	34.4	1.09	32.5	7.5
Main Effect Averages											
Pest Management											
CONV		142.2ab	107.2	15.6	12.9	184.6	124.0	30.0	1.13	34.0	7.9
RI		136.7b	103.3	15.5	12.8	178.0	120.6	31.3	1.16	33.6	7.9
BIO		151.0a	106.8	14.2	11.4	190.7	121.1	34.5	1.28	38.4	8.4
Soil Management											
Unamended		145.5	106.3	14.2	11.5	175.3	115.6	29.6	1.18	36.6	7.3
Amended		141.2	105.3	16.1	13.3	193.6	128.2	34.3	1.20	34.1	8.8
Variety											
Atlantic		155.2	110.5	16.8	13.5	207.5	135.6	34.5	1.29	40.7	8.7
Superior		131.5	101.1	13.5	11.2	161.4	108.2	29.3	1.09	29.9	7.4
ANOVA Results											
Pest Management		p<.05	ns	p<.1	p<.1	p<.1	ns	ns	ns	ns	ns
Soil Management		ns	ns	p<0.01	p<.01	p<.05	p<.05	p<0.05	ns	ns	p<.05
Variety		p<.01	p<.1	p<0.01	p<.01	p<.01	p<.01	p<0.05	p<.05	p<.01	p<.05
Interactions		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium; and Tot. = total, Tub. = tubers.

CONV = conventional RI = reduced input, and BIO = biological pest management systems.

- = Unamended, + = Amended.

[1] Based on analysis of haulm and tuber samples collected just prior to vine destruction.

Table 2.15. Uptake and removal of minor nutrients by the 1993 potato crop.

Pest Mgt. System	Soil Mgt. System	Nutrient Uptake by the Potato Crop (lbs/A)[1]											
		Al		B		Cu		Fe		Mn		Zn	
		Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers
Atlantic													
CONV	Unamended	9.4	0.5	0.089	0.035	0.104	0.059	10.0	0.565	1.03	0.067	0.241	0.089
CONV	Amended	13.2	0.4	0.109	0.038	0.114	0.055	13.4	0.526	0.87	0.063	0.232	0.086
RI	Unamended	9.1	0.4	0.087	0.033	0.092	0.053	9.0	0.620	1.19	0.064	0.228	0.084
RI	Amended	8.5	0.4	0.093	0.040	0.116	0.061	8.3	0.496	0.74	0.066	0.252	0.097
BIO	Unamended	8.7	0.4	0.088	0.035	0.794	0.068	9.1	0.515	0.81	0.071	0.216	0.096
BIO	Amended	10.7	0.8	0.122	0.050	0.821	0.063	11.2	0.926	0.73	0.073	0.236	0.097
Superior													
CONV	Unamended	10.2	0.4	0.079	0.029	0.109	0.047	10.7	0.494	0.82	0.061	0.234	0.101
CONV	Amended	7.9	0.4	0.085	0.038	0.089	0.051	8.4	0.549	0.61	0.057	0.236	0.124
RI	Unamended	11.8	0.4	0.083	0.032	0.102	0.052	10.4	0.498	0.95	0.062	0.245	0.109
RI	Amended	7.8	0.3	0.086	0.036	0.087	0.044	7.6	0.361	0.76	0.051	0.243	0.101
BIO	Unamended	9.2	0.4	0.077	0.029	0.582	0.056	9.3	0.455	0.62	0.058	0.232	0.100
BIO	Amended	9.1	0.4	0.089	0.034	0.658	0.051	9.1	0.495	0.52	0.059	0.220	0.101
Main Effect Averages													
Pest Management													
CONV		10.2	0.4	0.091	0.035	0.104b	0.053	10.6	0.534	0.83ab	0.062	0.236	0.100
RI		9.3	0.4	0.087	0.035	0.099b	0.052	8.8	0.494	0.91a	0.061	0.242	0.098
BIO		9.4	0.5	0.094	0.037	0.714a	0.060	9.7	0.598	0.67b	0.065	0.226	0.099
Soil Management													
Unamended		9.7	0.4	0.084	0.032	0.297	0.056	9.8	0.524	0.90	0.064	0.233	0.097
Amended		9.5	0.5	0.097	0.039	0.314	0.054	9.7	0.559	0.71	0.062	0.236	0.101

Table 2.15. Continued.

		Nutrient Uptake by the Potato Crop (lbs/A)[1]											
		Al		B		Cu		Fe		Mn		Zn	
Pest Mgt. System	Soil Mgt. System	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers	Tot.	Tubers
Variety													
Atlantic		9.9	0.5	0.098	0.039	0.340	0.060	10.2	0.608	0.90	0.068	0.234	0.092
Superior		9.3	0.4	0.083	0.033	0.271	0.050	9.3	0.475	0.71	0.058	0.235	0.106
ANOVA Results													
Pest Management		ns	ns	ns	ns	p<.01	ns	ns	ns	p<.05	ns	ns	ns
Soil Management		ns	ns	p<.05	p<.01	ns	ns	ns	ns	p<.01	ns	ns	ns
Variety		ns	p<.05	p<.01	p<.05	p<.1	p<.05	ns	p<.05	p<.01	p<.05	ns	p<.05
Interactions		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Al = aluminun, B = boron, Cu = copper, Fe = iron, Mn = manganese, Zn = zinc.

[1] Based on analysis of haulm and tuber samples collected just prior to vine destruction.

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

Rotation Crops

Barley grain and biomass yield

Barley grain yield was very low during 1991 (Table 2.16; 22 bu/A @ 12% moisture) due to late planting, dry weather, and unfavorable soil conditions. Yields did not differ significantly between the pest management and the soil management systems; however, significant differences were detected between experimental blocks. Block #1 produced yields that were nearly double those of the other three blocks. This strong block effect was probably due to initial differences in soil pH and soluble aluminum. Poor barley performance in 1991 was anticipated based on initial soil pH levels (see Appendix Table A1) and a liming program was initiated prior to planting during 1991 to correct this problem. Grain yields improved dramatically in subsequent years and were typical of those obtained commercially in the area (Table 2.16; e.g., 73, 67, and 74 bu/A @12% moisture during 1992, 1993, and 1994, respectively). Grain yields were not affected by pest or soil management system in any of the years, and no differences were detected between blocks. The improved yields in 1992 and subsequent years reflect higher rainfall, improved soil pH, and better fertility levels established after taking over the research site during 1991. Better timing of management practices (Appendix Table A5), especially planting, could further enhance our barley yields. Spring spreading of amendments has been a time-consuming field practice that has delayed planting of all crops in the study. We hope to alleviate this problem by spreading the manure during the fall of each year beginning during fall 1994.

Table 2.16. Dry matter yields within the barley rotation plots.

	----------- Barley ----------- (Pounds of dry matter/A)				Pounds of Dry Matter per Acre	
Year	Grain	Straw	Total	Harvest Index	Clover	Weeds
1991	932	1426	2358	0.40	---	---
1992	3078	3410	6488	0.48	232	157
1993	2848	2661	5509	0.50	298	133
1994	3148	2984	6132	0.53	272	243

Barley and clover dry matter yields did not differ among pest management systems during any of the growing seasons. Weed biomass yield differed significantly among pest management systems during 1992, 1993, and 1994 (see text for explanation of effects).

Aboveground dry matter production for barley varied between years similarly to grain yields. Dry matter production totaled 2358, 6488, 5509, and 6132 lbs/A for 1991, 1992, 1993, and 1994, respectively (Table 2.16). The barley crop returned 1426, 3410, 2661, and 2984 lbs/A of dry matter to the soil as crop residue in 1991, 1992, 1993, and 1994, respectively (Table 2.16). No significant differences were observed between the pest and the soil management systems in any of the years.

Clover was intercropped with the barley in each year of the study. Yields of aboveground clover biomass were not determined during 1991. At the time of barley harvest, yields of clover dry biomass were less than 300 lbs/A during 1992 to 1994 (Table 2.16). Clover biomass yields did not differ significantly between management systems in any year. The measured biomass yields were low, but would increase considerably from barley harvest until fall tillage. Unfortunately, late fall clover yields were not determined in any of the years.

Weed dry biomass at the time of barley harvest was measured during 1992 through 1994 (Table 2.16). Differences between the pest management systems were detected in each growing season. Weed biomass yields for 1992 were 78 lbs/A in the CONV system and 236 lbs/A in the RI system. The rotation plots of the BIO system were planted to green manure, rather than barley, during 1992. Weed biomass yields for 1993 were 42, 65, and 291 lbs/A for the CONV, RI, and BIO systems, respectively. Weed biomass yields differed even more dramatically between pest management system during 1994 at 13, 27, and 778 lbs/A for the CONV, RI, and BIO systems, respectively. These system effects were expected based on the half rate of herbicide used in the RI system and the elimination of herbicide use in the BIO system. Although there is no evidence to date of any weed effects on barley yields in this study, we are concerned about the long-term effects of these system differences on weed densities and seed populations in the soil. To help reduce these differences, beginning in 1995, we plan to add a cultivation operation just after weed emergence in the BIO system.

Green manure biomass yield and species composition

Based on samples collected in early October, the green manure crop (oats, peas, clover, and vetch) returned 6329, 6513, and 5774 lbs/A of aboveground dry biomass to the soil during 1992, 1993, and 1994, respectively (Figure 2.8). Based on these yields, the green manure crop provides a dramatic increase in dry matter returned to the soil compared to the barley rotation. Dry matter returned to the soil was higher by a factor of 1.7-fold compared to barley in 1992, 2.1-fold in 1993, and 1.6-fold in 1994 (Figure 2.8).

Species composition of the green manure mixture at final sampling varied considerably between years (Figure 2.9). Vetch was most prominent in the mixture during 1992, while peas dominated during 1993 and 1994. This shift was possibly due to differing rainfall patterns between the growing seasons and/or the shift from the Columbia variety to Trapper during 1993 and 1994. Because the green manure crop consists largely of legumes, the "quality" of the green manure residue differs dramatically from the barley residue. The result is that the green manure residue is much higher in nitrogen content than barley straw (approximately 3% for the green manure vs 1% for barley straw). The amount of nitrogen in the aboveground portions of the green manure crop would be much larger than that in the portions of the barley crop returned to the soil. At 3.28% nitrogen, the 1992 green manure crop returned 208 lbs/A of aboveground nitrogen to the soil, while only 26 lbs/A would be returned to the soil in the barley crop residue (0.77% nitrogen during 1992). At 2.74% nitrogen, the 1993 green manure crop returned 178 lbs/A of aboveground nitrogen to the soil, while only 26 lbs/A was returned to the soil in the 1993 barley straw (0.97% N). The higher nitrogen content of the legume residues is expected to result in rapid decomposition and release of nutrients

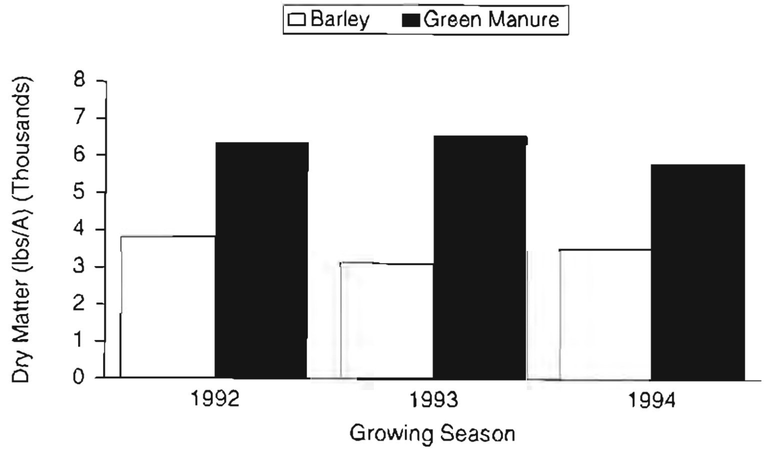


Figure 2.8. Dry matter returned to soil by rotation crop, 1992–1994 (aboveground dry matter only).

to subsequent crops. Nitrogen analyses for the 1994 rotation crops are not available at this time of this report.

Weed biomass constituted a small portion of the total green manure biomass at the final sampling during 1992, 1993, and 1994 (Figure 2.9) and did not differ significantly between the pest management systems of the experiment. The lack of pest management system differences was expected because herbicides are not used for weed control in the green manure crop in any pest management system; however, higher weed biomass values might have been expected in the BIO plots because more weed growth and weed seed production occurs within the BIO potato plots than in the CONV or the RI. The data indicate that the green manure crop has effectively suppressed weed growth in this study and has been much more effective at preventing weed growth than the barley rotation crop.

Soils

Soil pH and nutrient analyses

Soil samples were collected from each plot before treatment application in spring 1991 and in October of 1991, 1992, 1993, and 1994. Macro- and secondary nutrient content, pH, and cation exchange capacity were determined for each of these samples. Results from the 1994 sampling are not available at the time of this writing. Additional, soil samples collected during spring 1990 provided a basis for blocking experimental plots into groups with similar soil conditions (Appendix Table A1). Soil test results in the May 1991 sampling represent initial soil conditions at the start of

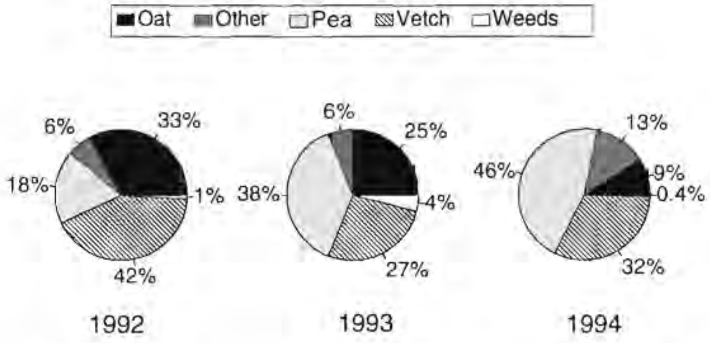
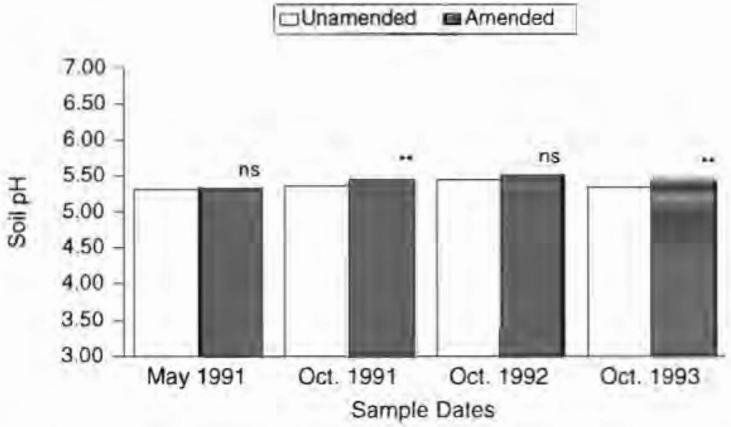


Figure 2.9. Species composition of green manure rotation crop. Final harvest data (early October).

the experiment and before treatment application was initiated. At this sampling, there were no significant pH or nutrient content differences between the pest and soil management systems, varieties, or rotation entry point factors (data not presented). Differences in pH and soil magnesium levels were detected between the blocks (i.e., fields) of the experiment. Soil pH ranged from 5.4 in block #1 to 5.0 in block #4. Soil magnesium ranged from 361 lbs/A (27.5% base saturation) in block #1 to 169 lbs/A (14.0% base saturation) in block #4. Soil calcium (range 1317 lbs/A, 59.5% base saturation in block #1 to 919 lbs/A, 44.9% base saturation in block #4) and potassium (range 340 lbs/A, 8.1% base saturation in block #3 to 264 lbs/A, 6.2% base saturation in block #1) differed considerably between the blocks of the experiment. These latter soil characteristics, however, were also quite variable within blocks. Despite the varied soil test results across the blocks of the experiment, all results fell within normal levels for potato production in Maine. Initiation of our differential liming program during spring 1991 (Appendix Table A1) eliminated most soil test differences between blocks in subsequent samplings (data not presented). Only soil calcium levels showed dramatic differences between blocks at the 1993 sampling (range 926 lbs/A in block #2 to 1430 lbs/A in block #4).

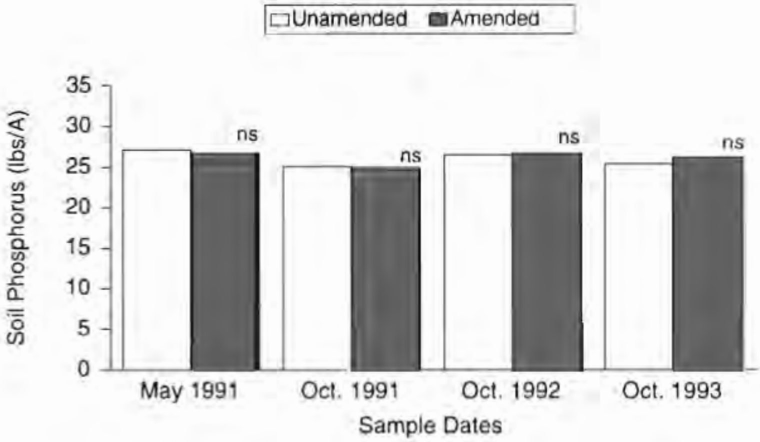
After treatment application was initiated, soil management system was the primary factor influencing soil nutrient analysis over the course of this study. The amended system slightly increased soil pH (Figure 2.10) in two of three growing seasons, but did not significantly affect the soil test phosphorus levels (Figure 2.11). The latter observation is surprising because analysis of the organic amendments (Appendix Table A4) indicated that phosphorus loading in the amended system would be considerably more than that in the unamended system. The lack of soil test response is an indication that phosphorus within the organic amendments is rapidly converted to chemical forms within the soil that are not readily available for plant uptake. Alternatively, some of the phosphorus may be in organic or other forms in the soil that may remain available for crop uptake, but are not measurable with the current soil test procedure.

The manure and compost treatments used in these studies are good sources of potassium, magnesium, and calcium (Appendix Table A4). Consequently, as the experiment progressed, the amended system significantly increased soil test levels of these nutrients compared with the unamended system (Figures 2.12 to 2.14). Elevated soil calcium and magnesium levels detected in both soil



Within sample dates:* and ** indicate significant effect at p<0.05 and 0.01, respectively.

Figure 2.10. Soil pH, 1991–1993 (averaged over pest management, variety, and rotation entry point).

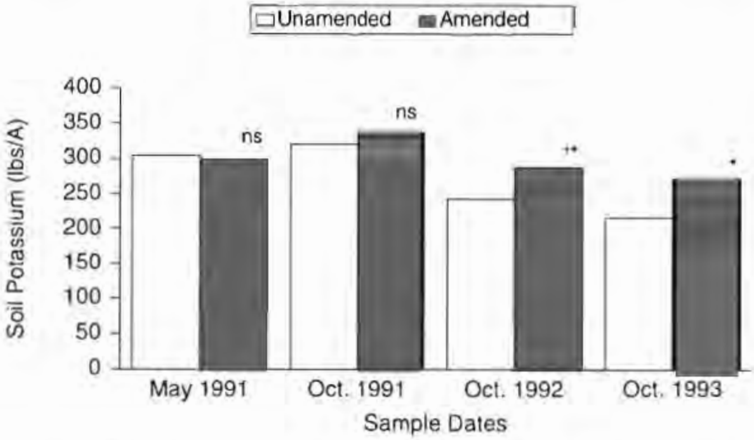


Within sample dates: * and ** indicate significant effect at p<0.05 and 0.01.

Figure 2.11. Phosphorus soil test levels, 1991–1993 (averaged over pest management, variety, and rotation entry point).

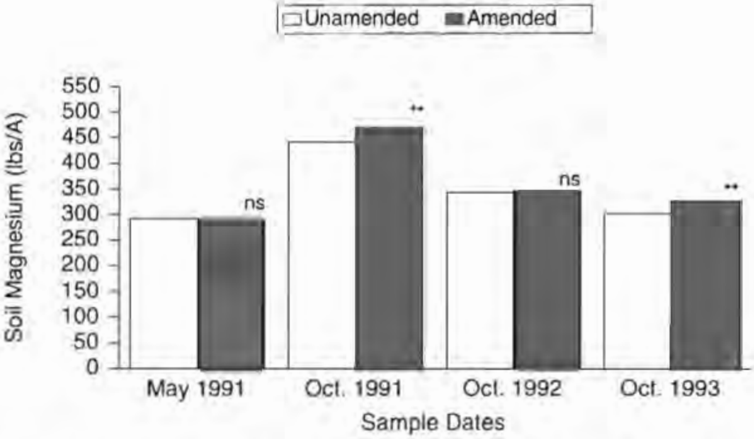
management systems during fall 1991 probably reflect partial extraction of these nutrients from undissolved limestone applied during the previous spring. The significant effect of soil management system on soil potassium levels has been particularly dramatic in this study and potentially is very important. Among crops, potato is a heavy user of soil and fertilizer potassium. A typical crop can remove up to 160 lbs/A of potassium in the tubers. Inadequate potassium availability can dramatically reduce tuber size and yields. Based on these concerns and declining soil potassium levels in the unamended system, the rate of potash fertilizer applied in this system was increased by 80 to 160 lbs/A during the 1994 growing season (Appendix Table A2; rate of application depended on the experimental block).

Soil management system has significantly altered effective soil cation exchange capacity (CEC) in two of three years since treatments were initiated (Figure 2.15). Compared with the unamended system, the amended system significantly increased effective CEC in two of three growing seasons. Over the years 1991, 1992, and 1993, effective CEC increased by 9.4%, 4.0%, and 6.9%, respectively. Since effective CEC of this soil type is partially dependent on pH, the slight increases in effective CEC within the amended system may be related to the small pH increase detected in this system (Figure 2.10). Alternatively, or in combination with this effect, organic molecules released during the breakdown of the



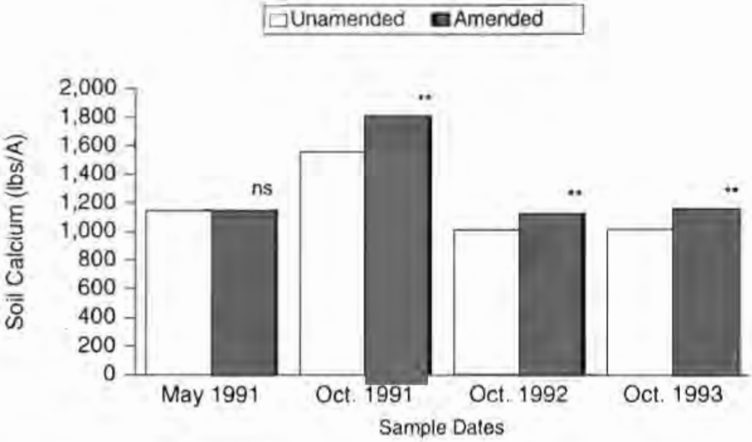
Within sample dates: * and ** indicate significant effect at $p<0.05$ and 0.01, respectively.

Figure 2.12. Potassium soil test levels, 1991–1993 (averaged over pest management, variety, and rotation entry point).



Within sample dates: * and ** indicate significant effect at p<0.05 and 0.01, respectively.

Figure 2.13. Magnesium soil test levels, 1991–1993 (averaged over pest management, variety, and rotation entry point).

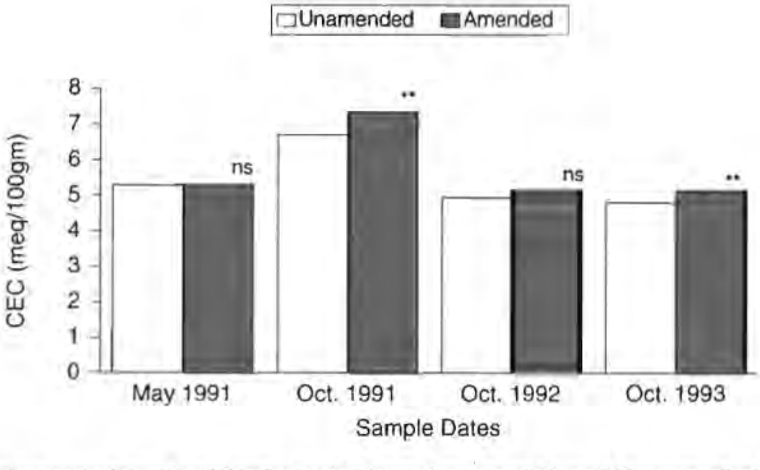


Within sample dates: * and ** indicate significant effect at p<0.05 and 0.01, respectively.

Figure 2.14. Calcium soil test levels, 1991–1993 (averaged over pest management, variety, and rotation entry point).

organic amendments may be positively contributing to effective CEC.

Percent saturation of the cation exchange sites by various soil nutrients has shifted slightly over the course of the experiment. Data from samples collected before treatment application in 1991 and after the 1993 growing season are presented (Figure 2.16). Initially, percent saturation of the exchange sites with potassium, calcium, magnesium, and acidity showed no significant differences between the soil management systems. After three years of treatment application, percent potassium and calcium saturation were significantly higher in the amended system than in the unamended system. Percent acidity was significantly lower in the amended system. Over the three years of treatment application, potassium saturation remained approximately constant in the amended system, while percent calcium and magnesium saturation rose slightly. Percent magnesium saturation also rose slightly in the unamended system; however, percent potassium saturation showed a substantial decline. As was noted earlier, the declining potassium levels in this system were the basis for increasing the rate of potash fertilizer applied during the 1994 growing season. The increased magnesium saturation observed in both soil management systems was due to the initial use of dolomitic limestone in our liming program.

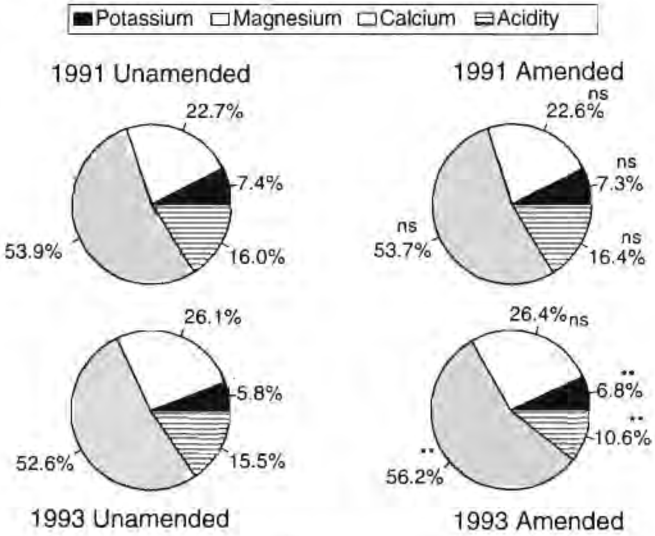


Within sample dates: * and ** indicate significant effect at $p<0.05$ and 0.01, respectively.

Figure 2.15. Soil cation exchange capacity, 1991–1993 (averaged over pest management, variety, and rotation entry point).

Besides the soil management effects and block effects described above, pH and nutrient analyses were often affected by rotation crop entry point and sometimes by the interaction between two or more experimental factors. These effects were small and inconsistent over growing seasons when compared to the effects observed for the soil management systems. Significant differences in crop rotation entry point were detected for soil pH (1991–1993), CEC (1991–1993), phosphorus (1992), potassium (1991–1992), magnesium (1991–1992), percent magnesium saturation (1992), calcium (1991–1992), and percent calcium saturation (1992–1993). These rotation crop entry point effects are likely due to the combined effect of rotation crop, growing season and fall tillage practices, organic amendment application program, and liming program. Interaction of system factors showed no consistent effects between the three seasons. As expected, pest management system and variety have not consistently affected soil nutrient analyses.

The results of soil tests for nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) are reported in Tables 2.17 and 2.18.



Within years: ** indicate significant soil management effect at p<0.01.

Figure 2.16. Percent saturation of soil cation exchange capacity. Soil management effects (averaged over pest management, variety, and rotation entry point).

Samples collected during 1993 (28 June–7 July), while barley was still the rotation crop in the amended system, indicated that soil NO_3-N and NH_4-N concentrations were higher in the unamended plots than in the amended plots. In 1994 (sample dates, 1–20 June), with the green manure rotation crop incorporated as part of the amended system, the results were reversed, significantly so for NO_3-N. The 1994 results are in line with what is hypothesized, in that the green manure rotation crop should contribute extensively to the readily available supply of nitrogen in the soil. The compost should also enhance the soil cation exchange capacity (CEC), thereby improving nutrient retention and availability to plants.

Soil organic matter

Readily oxidizable soil organic matter increased significantly in the amended system compared with the unamended system (Figure 2.17). No differences were observed between the two soil management systems prior to initial treatment application (Figure 2.17). Sampling for this soil property took place in the spring of each year just before amendment application; therefore, the significant increases noted in 1992 (13.4%) and 1993 (13.5%) represent measurable increases after just one and two years of treatment application, respectively. The increases are not surprising considering that the amended system receives 10 tons/A of compost each year and 20 tons/A of manure before each potato crop. The relationship between these increased organic matter levels and other soil properties, nutrients, and physical characteristics, as the project progresses, should be particularly interesting.

Block, pest management system, variety, and crop rotation entry point have not consistently had significant effects on soil organic matter in this study (data not presented). Interactions between the experimental factors also have generally not been

Table 2.17. Soil nitrate-nitrogen analyses, 1993–1994.

Treatment	1993		1994	
	Mean (ppm)	Variance $(ppm)^2$	Mean (ppm)	Variance $(ppm)^2$
Unamended	35.6	224.3	17.3	105.0
Amended	25.2	54.7	36.8	351.0
Significance Test:	**	**	**	**

[1]Within years the significance tests were based on the analysis of variance using the following alpha levels: * and ** indicate significance at $p<0.05$ and 0.01, respectively.

Table 2.18. Soil ammonium-nitrogen analyses, 1993–1994.

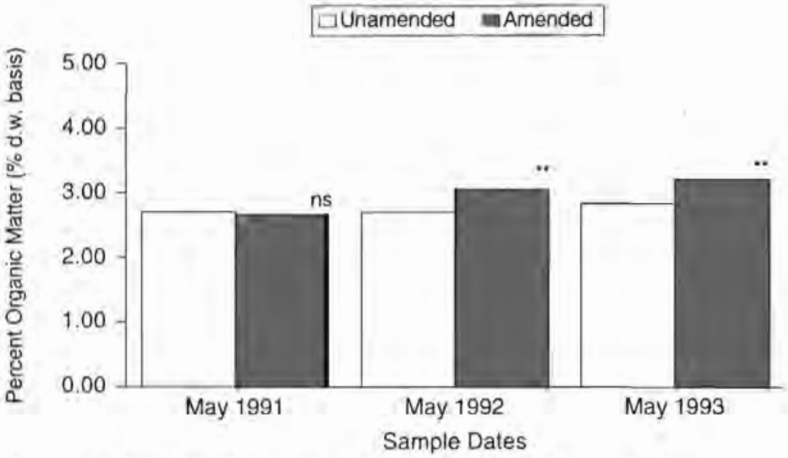
Treatment	1993 Mean (ppm)	1993 Variance (ppm)^2	1994 Mean (ppm)	1994 Variance (ppm)^2
Unamended	17.0	123.0	5.5	9.8
Amended	11.2	20.8	8.6	9.2
Significance Test[1]:	**	**	**	*

[1] Within years the significance tests were based on the analysis of variance using the following alpha levels: * and ** indicate significance at $p<0.05$ and 0.01, respectively.

significant. Soil management system is therefore the primary experimental factor influencing soil organic matter content in this study.

Soil physical characteristics

Water-stable aggregate content is a measure of soil structure, the aggregation of sand, silt, and clay constituents into larger units. Soil structure is an important determinant of aeration, water movement, and root penetration within soils. Since soil organic matter influences soil aggregation and structure, improved soil structure is expected as soil organic matter content increases.



Within sample dates: ** indicate significant soil management effect at $p<0.01$.

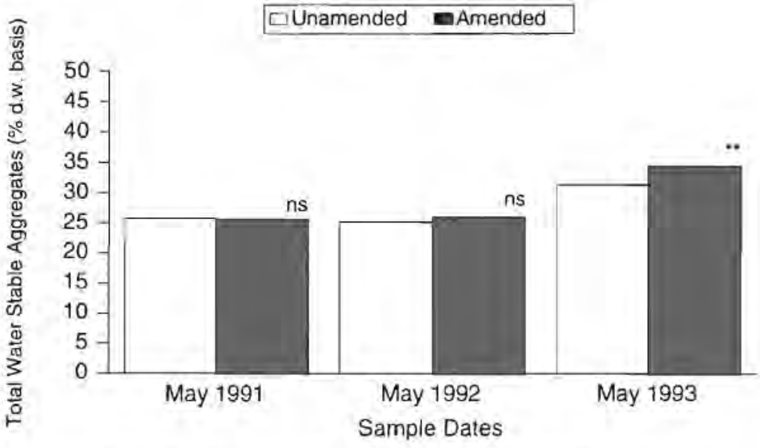
Figure 2.17. Soil organic matter, 1991–1993 (averaged over pest management, variety, and rotation entry point).

Because of this, we hypothesized that the water-stable aggregate content should increase within the amended soil management system. Samples collected during May 1993 indicated that water-stable aggregate content was significantly higher in the amended system compared with the unamended system (Figure 2.18). The significant increase detected in 1993 (9.9%) represents a measurable increase after two years of system application. No differences were observed between the two soil management systems before initial treatment application and after one year of treatment application (the May 1991 and 1992 samples). The improvement documented to date is small; however, if continued over time, it would provide strong evidence that the amended soil management system is beneficially affecting soil structure.

In addition to soil management effects on soil water-stable aggregate content, block differences were present at the start of the experiment and have persisted through the two subsequent samplings. Block #1 has considerably higher water-stable aggregate content than the other blocks and is also producing the highest tuber yields (data not presented). Unfortunately, it is not possible to determine whether the yield differences are directly due to soil physical properties. Significant differences in crop rotation entry point have also been present in the 1992 and 1993 samplings. Water-stable aggregate content was significantly higher coming out of the rotation crop portion of the two-year cropping cycle than out of previous potato crops (26.6% vs 24.4% during May 1992, $p<0.05$; 35.8% vs 29.7% during May 1993, $p<0.01$). These effects are likely due to the combined effect of rotation crop, growing season, fall tillage practices, and organic amendment application program. As expected, pest management system has not consistently affected water-stable aggregate content; however, average values in the plots of the BIO system were slightly lower than those in the other pest management systems at the start of the experiment and have remained consistently lower throughout the study.

Bulk density

The results of soil bulk density testing are presented in Table 2.19. There were no significant differences in bulk density means and variances between the unamended and amended systems. These results are not surprising given the short duration of the study and relatively small organic matter loading rates. With these loading rates it seems unlikely any permanent structural improvements would be observed in this short period. It is possible that differences may be observed in the early season, either after incorporation or after planting. Means and variances between



Within sample dates; ** indicates significant soil management effect at $p<0.01$.

Figure 2.18. Soil water-stable aggregates, 1991–1993 (averaged over pest management, variety, and rotation entry point).

years were not compared as there were known sampling discrepancies between the three seasons. These discrepancies included different sampling periods (mid- to late season), different sampling personnel, different soil moisture conditions (very dry to fairly moist) and plot differences due to rotation (1992 and 1994 vs 1993).

Soil moisture retention

Due to the nature of the information produced, results of moisture retention curve analyses cannot readily be presented concisely. Therefore, only representative examples of retention curves are presented. Figure 2.19 (a, b, c) provides a snapshot of typical pressure/moisture content responses to the addition of organic amendments the soils. Exercise caution in extrapolating this information to any particular situation, as each curve is the result of a single sample composited from a plot at a single sample date. Samples collected in 1994 were not available for this report.

Each section of Figure 2.19 shows pressure/moisture content relationships for various amendment combinations for a given block. These curves are indicative of drying-type (moisture release) curves; wetting curves were not determined. Amended plots are indicated by dashed lines while unamended plots are represented by solid lines. Overall, amended soils had higher moisture contents than did the unamended at the given test pressures. This was

Table 2.19. Soil bulk density analyses, 1992–1994.

Treatment	1992 (n = 48)		1993 (n = 12)		1994 (n = 16)	
	Mean (g/cm³)	Variance (g/cm³)²	Mean (g/cm³)	Variance (g/cm³)²	Mean (g/cm³)	Variance (g/cm³)²
Unamended	1.27	0.010	1.06	0.0152	1.13	0.0119
Amended	1.24	0.0200	1.00	0.0190	1.12	0.0071
Significance Test[1]	ns	ns	ns	ns	ns	ns

[1] Within years the significance tests were based on the analysis of variance using the following alpha levels: * and ** indicate significance at $p<0.05$ and 0.01, respectively.

especially true in the low pressure portion of the curves. More important, there was no consistent change in available moisture between systems. Available moisture is that moisture released between two given pressures. This would appear graphically as slope differences between the individual curves. Greater slopes would indicate higher moisture release; flatter slopes would indicate lower moisture release. Although slope differences did exist, the differences were not consistent between systems.

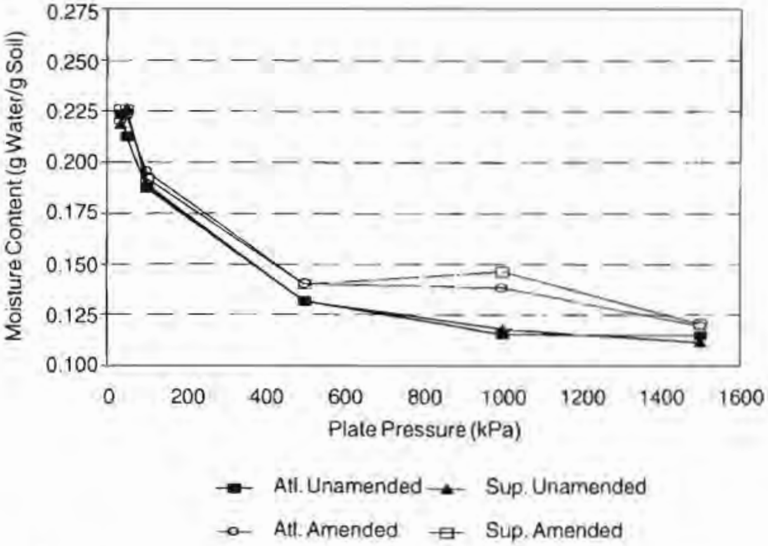


Figure 2.19a. Moisture retention curves, block 1, reduced input, 1993.

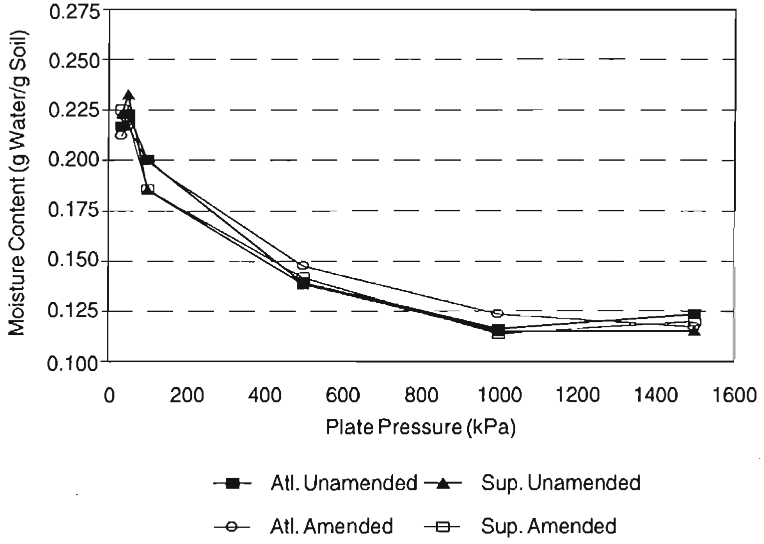


Figure 2.19b. Moisture retention curves, block 3, biological, 1993.

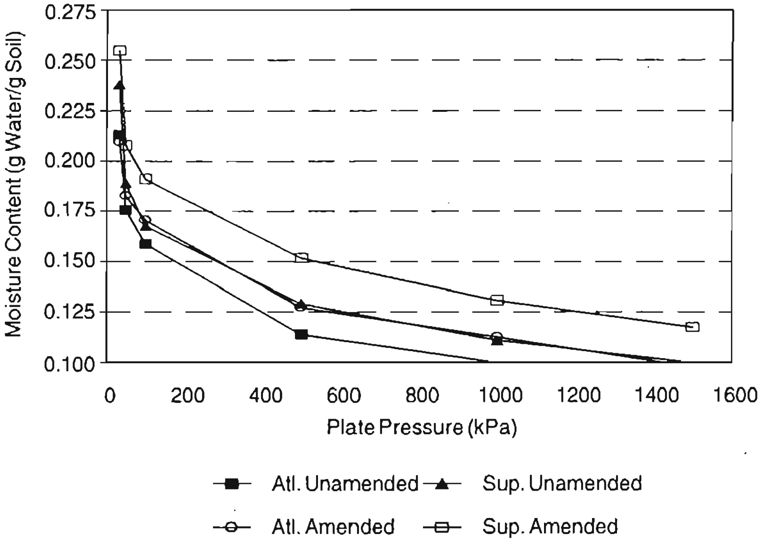


Figure 2.19c. Moisture retention curves, block 4, conventional, 1993.

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III. Weed Dynamics

Matt Liebman and Eric R. Gallandt[1]

INTRODUCTION

Herbicides are widely used in commercial potato production systems in Maine. Although these materials can be extremely effective for controlling weed interference against crops, growing concerns about water contamination, worker health and safety, and rising costs of farm production have increased interest in mechanical and cultural methods of weed control and in reduced rates of herbicide application. Through studying effects of crop rotation, pest management, and soil management systems on weed population dynamics, we hope to gain an integrated understanding of weed management from an agroecosystem perspective.

Weed dynamics were studied from 1991 to 1994 in the 48 of the 96 treatment plots that were planted with Atlantic potatoes and associated rotation crops (barley/red clover or the multispecies green manure [oat/pea/hairy vetch]; these systems are hereafter referred to as the barley and green manure crops, respectively). Our objectives were to measure the effects of different management systems on the species composition, density, and aboveground biomass (dry matter production) of weeds growing in the field and the species composition and density of readily germinable weed seeds in the soil.

METHODS

Weed control practices associated with the different crop-pest management treatment combinations are shown in Table 3.1. Weed population density and aboveground biomass were measured in potato plots on 7 August 1991, 13 August 1992, 16 August 1993, and 1 August 1994, and in rotation crop plots on 12 July 1991, 28 July 1992, 29 July 1993, and 19 July 1994. Aboveground weed material was clipped from eight 2.7-ft^2 sampling quadrats in each potato plot and five 2.7-ft^2 quadrats in each rotation crop plot. Plant material from the quadrats was sorted by species, dried, and weighed.

Density of readily germinable weed seeds in the soil was estimated by removing soil cores from each plot immediately before or just after crops were planted. Ten 3.25-in.-diameter bucket auger cores were taken from each plot to a depth of 4 in. on 23–24

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[1] Special thanks to Sue Corson, former scientific technician, for her work on the weed dynamics of this project.

Table 3.1. Weed management practices used in the different crop-pest management treatment combinations.

Crop	Year	Pest Management System	Herbicide(s)	Cultivation
Potatoes	1991	CONV	metribuzin, 0.50 lb ai/A	2 hillings
		RI	None	1 cultivation +2 hillings
		BIO	None	1 cultivation +2 hillings
	1992	CONV	metribuzin, 0.50 lb ai/A + paraquat, 0.48 lb ai/A + X-77 surfactant, 0.125% (v/v)	2 hillings
		RI	None	1 cultivation +2 hillings
		BIO	None	1 cultivation +2 hillings
	1993	CONV	metribuzin, 0.50 lb ai/A + paraquat, 0.48 lb ai/A+ X-77 surfactant, 0.125% (v/v)	2 hillings
		RI	metribuzin, 0.25 lb ai/A + paraquat, 0.24 lb ai/A + X-77 surfactant, 0.125% (v/v)	1 cultivation +2 hillings
		BIO	None	1 cultivation +2 hillings
	1994	CONV	metribuzin, 0.50 lb ai/A + paraquat, 0.48 lb ai/A+ X-77 surfactant, 0.125% (v/v)	1 hilling
		RI	metribuzin, 0.25 lb ai/A + paraquat, 0.24 lb ai/A + X-77 surfactant, 0.125% (v/v)	1 cultivation +1 hilling
		BIO	None	2 cultivation +1 hilling
Barley	1991	CONV	MCPA, 0.25 lb ai/A	None
		RI	None	None
		BIO	None	None
	1992	CONV	MCPA, 0.25 lb ai/A	None
		RI	MCPA, 0.125 lb ai/A	None
		BIO	None	None
	1993	CONV	MCPA, 0.25 lb ai/A	None
		RI	MCPA, 0.125 lb ai/A	None
		BIO	None	None
	1994	CONV	MCPA, 0.25 lb ai/A	None
		RI	MCPA, 0.125 lb ai/A	None
		BIO	None	None
Green Manure	1992–1994	CONV	None	None
		RI	None	None
		BIO	None	None

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

May 1991, 21–22 May 1992, 27 May 1993, and 3–4 June 1994. Cores were then composited by plot, sieved through 0.25-in. mesh hardware cloth to remove stones and coarse fragments, and spread over fine vermiculite. Soil from the ten cores was spread in flats to form a layer approximately 1 in. thick, placed in a greenhouse, and watered gently twice daily. In 1994 the procedure was modified because conditions at sampling resulted in a greater volume of soil than in previous years. Samples in 1994 were pooled, mixed, and divided in half by weight. One half of the soil collected was spread in flats. Seedlings were identified, counted, and pulled over a four- to six-week period before soil was dried, crumbled, mixed, and rewatered to stimulate a new flush of germination. This cycle was repeated four times each year. Density of readily germinable seeds of each species was calculated as the cumulative emergence obtained from the soil flats divided by the field surface area of ten bucket auger cores in 1991–1993, and five bucket auger cores in 1994. Data analysis focused on the seedbank at the start of the 1994 cropping season, and changes in the seedbank between the start of the experiment in 1991 and 1994.

To test for differences between treatments in weed density and biomass production, data were analyzed using split plot analysis of variance. Data were transformed before analysis to meet assumptions of homogeneity of variance; a !(x+1) transformation was used for density data and a $\log_e(x+1)$ transformation was used for biomass data. The main plot factor used in the analyses was pest management system (conventional [CONV] vs reduced input [RI] vs biological [BIO]); subplot factors were entry point into the rotation (potato vs rotation crop phase), and soil management system (compost and manure amended, green manure rotation crop vs unamended, barley rotation crop). Treatment means were separated statistically using single degree of freedom contrasts and Fisher's Least Significant Difference test. Significance was set at the $p<0.05$ level. Relationships between weed density, weed biomass production, and crop yield were examined using analysis of covariance and multiple regression techniques.

RESULTS AND DISCUSSION

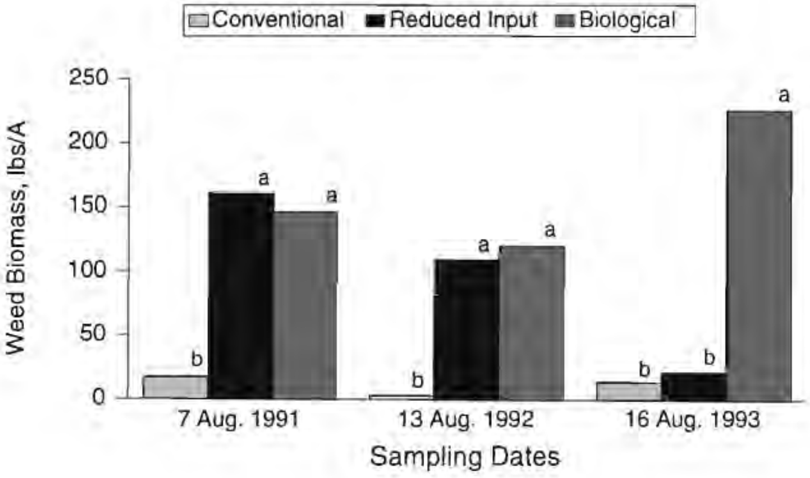
Weed Biomass in Potatoes

During the four years of measurements, weed biomass in potato plots was dominated by common lambsquarters (*Chenopodium album* L.), barnyardgrass (*Echinochloa crusgalli* [L.] Beauv.), and hempnettle (*Galeopsis tetrahit* L.). There was a considerable amount of Japanese millet (*Echinochloa frumentacea* [Roxb.] Link) in 1991, which volunteered from the 1990 cover crop. Birdsrape mustard (*Brassica rapa* L.) and wild mustard (*Brassica kaber* [DC] L. C. Wheeler) were important weeds in the BIO system in 1992.

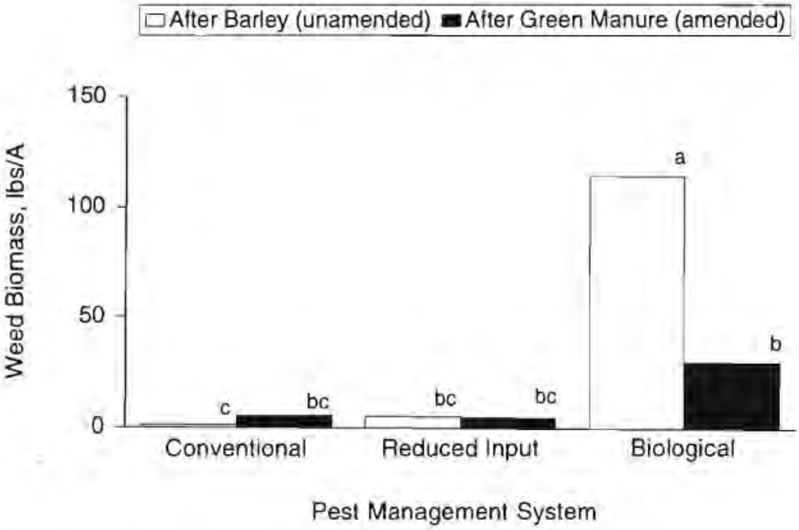
Weed biomass in potatoes did not differ between the two soil management systems (i.e., barley/unamended and green manure/amended) in 1991 through 1993. In contrast, significant differences in weed growth were observed between pest management systems during this period (Figure 3.1a). In 1991 and 1992, there was significantly more weed growth in the RI and BIO pest management systems than in the CONV system (Figure 3.1a). In these years, no herbicide was applied to potatoes in the RI or BIO systems; a full rate of herbicide was applied to the CONV system (Table 3.1).

The impact of herbicide application is further emphasized by results from 1993 (Figure 3.1a) and 1994 (Figure 3.1b), in which the CONV system received a full rate application, the RI system received a half-rate application, and the BIO system was not treated with herbicides. Weed biomass was significantly greater in the BIO system in 1993 than in the RI or the CONV systems. In 1994, total weed biomass in potatoes was affected by an interaction between pest management and soil management systems (Figure 3.1b). This interaction was highly significant ($p<0.001$) for lambsquarters, which, based on mass, was the dominant species in potatoes (data not presented). Contrasts (1df) revealed an interaction ($p<0.01$) between pest management systems with (CONV and RI) and without herbicides (BIO) and soil management systems. There was no significant difference between low (RI) and higher (CONV) herbicide rates.

Total weed biomass in 1994 was higher in BIO potatoes following barley without soil amendments than following green manure with soil amendments. In contrast, in CONV and RI potatoes, total weed biomass was low and was not affected by soil management system (Figure 3.1b). The reduced amount of weed biomass in BIO potatoes following green manure (29 lb/A) compared to following barley (114 lb/A) is noteworthy because in previous years soil management did not have an effect on total weed biomass. The reduction in total weed biomass in this treatment is partially due to a reduction in total weed density (see Table 3.2) and also the result of smaller individual weeds (e.g., in BIO potatoes, weed per plant biomass was about 50% lower following green manure than following barley [data not presented]). The cause of this effect is not



a. 1991–1993



b. 1 August 1994

Figure 3.1. Pest management system effects on aboveground weed biomass (dry matter basis) production in potatoes. Data for 1991–1993 (a) are averaged over soil management systems (rotation crop and soil amendment factors), whose effects were not significant, while in 1994 (b) there was a significant interaction between pest and soil management systems. Within each year, means accompanied by the same lowercase letter are not significantly different.

Table 3.2. Pest management system effects on weed densities in potatoes. Because there was no pest management system × soil management system interaction in 1991–1993, data presented for these years are averaged over rotation crop and soil amendment factors. In 1994 interactions between pest and soil management systems occurred. Within each column for each year, means followed by the same lowercase letter are not significantly different.

Pest Management System	Sampling Date	Common Lambsquarters	Barnyardgrass + Japanese Millet	Low Cudweed	Total
		# per sq. ft			
CONV	7 Aug 1991	0.1 b	2.2 ab	0 a	2.3 a
RI	7 Aug 1991	0.3 a	1.8 b	0 a	2.3 a
BIO	7 Aug 1991	0.1 ab	5.4 a	0 a	5.8 a
CONV	13 Aug 1992	5.4 a	3.1 a	2.7 b	13.7 a
RI	13 Aug 1992	4.0 ab	2.3 a	5.3 a	14.0 a
BIO	13 Aug 1992	2.1 b	1.2 a	2.7 b	11.6 a
CONV	16 Aug 1993	0.8 b	1.8 a	0.4 a	4.1 a
RI	16 Aug 1993	4.7 a	1.1 a	0.1 b	6.5 a
BIO	16 Aug 1993	2.8 ab	0.8 a	0.3 ab	4.4 a

Pest Mgt. System/ Soil Mgt. System	Sampling Date	Common Lambsquarters	Barnyardgrass + Japanese Millet	Low Cudweed	Total
		# per sq. ft			
CONV/barley (-)	1 Aug 1994	1.6 b	0.3 a	0.0 a	2.7 b
CONV/green manure (+)	1 Aug 1994	3.9 ab	0.7 a	0.0 a	5.2 ab
RI/barley (-)	1 Aug 1994	2.2 ab	0.1 a	0.0 a	3.0 b
RI/green manure (+)	1 Aug 1994	3.3 ab	0.3 a	0.0 a	4.9 ab
BIO/barley (-)	1 Aug 1994	4.7 a	0.3 a	0.0 a	6.3 a
BIO/ green manure (+)	1 Aug 1994	1.8 b	0.2 a	0.0 a	3.3 b
ANOVA					
Pest management system		ns	ns	ns	ns
Soil management system		ns	ns	ns	ns
interaction		$p<0.01$	ns	ns	$p<0.01$

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

(-) = without compost and manure amendments.

(+) = with compost and manure amendments.

known. The weeds may be exhibiting reduced density and biomass because of allelochemicals released from the green manure. Alternatively, the synthetic fertilizer application in potatoes following barley, about twice the amount applied to the green manure/ amended system, may have promoted early weed emergence leading to seedlings that were well established and therefore less susceptible to cultivation. Finally, compared to the barley unamended system, the green manure may be promoting a more vigorous potato crop that is better able to compete with weeds.

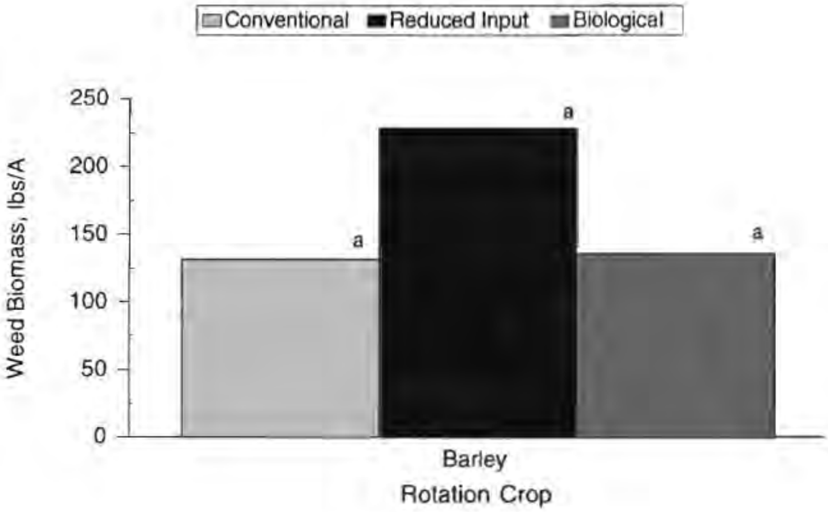
Weed growth at the August sampling dates never exceeded 250 lb/A in any of the three pest management systems. Examination of the relationship between weed growth and potato yield in 1993 (when potato plants in all treatments were free of nitrogen stress) showed no significant relationship between weed growth and crop yield, i.e., weedier plots were not associated with lower potato yields. Similarly, in 1994, there was no relationship between tuber yield and weed density or biomass. However, to accurately assess weed effects, yields must be compared to weed-free subplots. These measurements will be a high priority in future years. The greater amount of weed biomass in the BIO system suggests that more attention needs to be placed on cultivation equipment and technique to limit late-season weed growth, which can interfere with harvest operations and contribute to future weed problems. Growers who wish to reduce but not eliminate herbicide use should note the successful weed control obtained with reduced rate herbicide application in the RI system in 1993 (Figure 3.1a) and 1994 (Figure 3.1b).

Weed Biomass in Rotation Crops

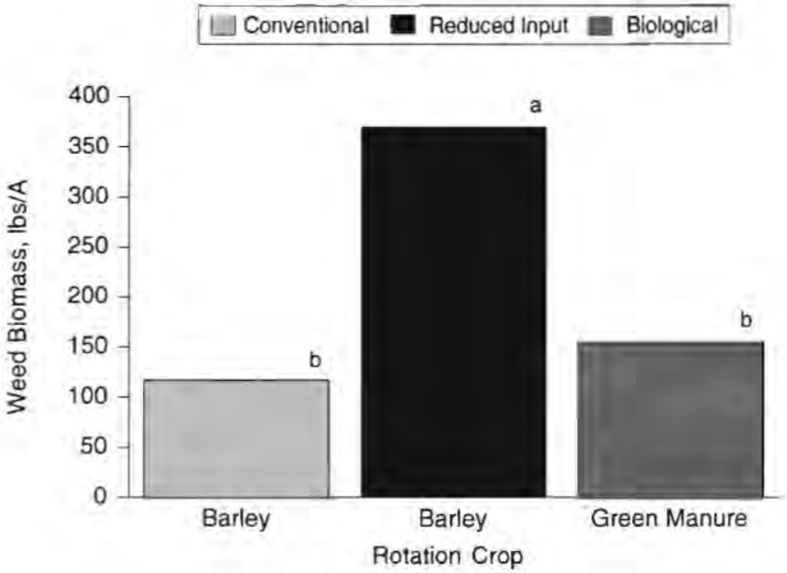
During each of the four years, weed biomass production in rotation crops was dominated by common lambsquarters, barnyardgrass, and hempnettle; a considerable amount of volunteer Japanese millet was also present in 1991.

In 1991, barley was grown as the rotation crop in all three pest management systems. No significant differences in weed growth were observed between BIO, RI, and CONV systems, despite application of herbicide to the CONV treatment (Figure 3.2a). Soil amendments had no significant effect on weed biomass.

In 1992, barley was used as the rotation crop for the CONV and RI pest management systems, and the multispecies green manure mixture (oat, pea, and hairy vetch) was used as the rotation crop in the BIO system. Application of soil amendments to potatoes preceding the 1992 rotation crops did not significantly affect weed growth

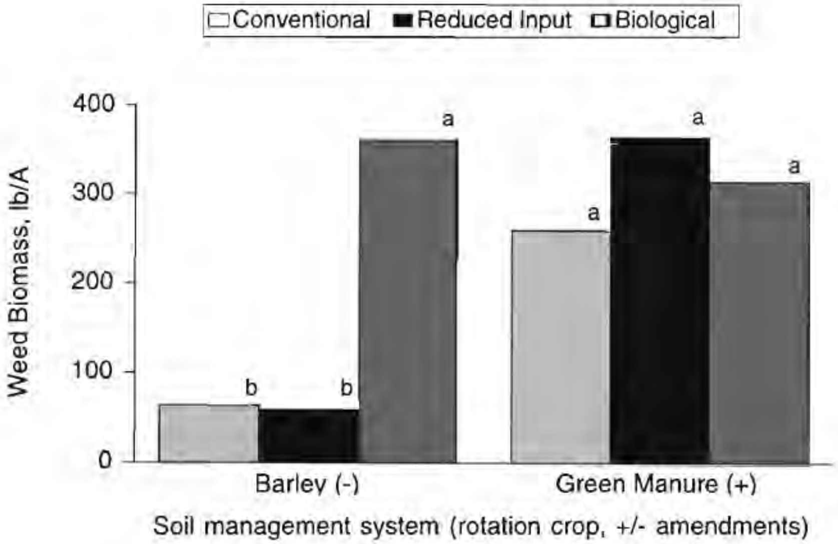


a. 12 July 1991

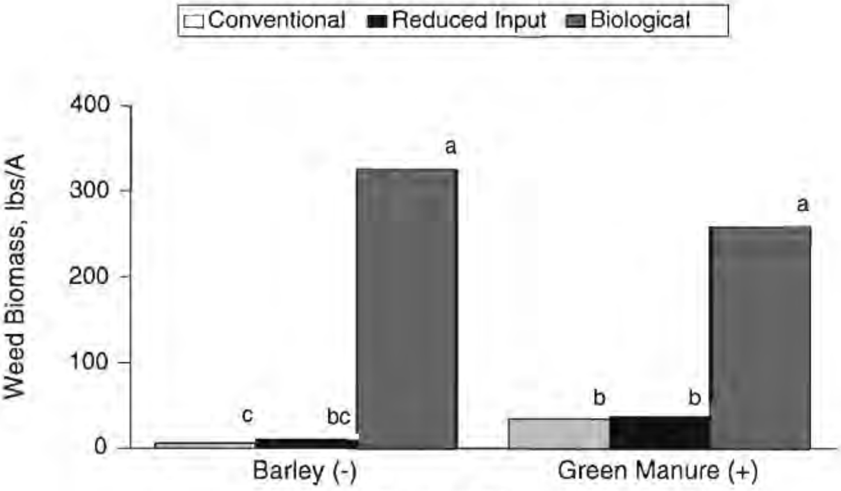


b, 28 July 1992

Figure 3.2. Pest and soil management systems effects on weed biomass (dry matter basis) production in rotation crops. Data presented for 1991 (a) and 1992 (b) are averaged over the soil amendment treatment, which had no significant effects.



c. 29 July 1993



d. 19 July 1994

Figure 3.2 (cont.). Pest and soil management systems effects on weed biomass (dry matter basis) production in rotation crops. In 1993 (c) and 1994 (d), soil amendments (compost and manure) were applied to rotation sequences that included the green manure crop (i.e., the amended soil management system), and there was a significant pest management system x soil management system interaction. Within each year, means accompanied by the same lowercase letter are not significantly different.

in the rotation crops. Significant differences in weed growth were observed between pest management systems, however (Figure 3.2b). Weed growth was greater in the RI system than the BIO and CONV systems. Barley in the RI and CONV systems received half-rate and full-rate applications of herbicide, respectively, while weed suppression in the green manure crop of the BIO system was accomplished only by crop competition.

In 1993, weed growth in rotation crops was affected by an interaction between pest management and soil management systems (Figure 3.2c). Green manure and barley were grown in each pest management system; beef manure and compost were applied to potatoes preceding the green manure crop, but not to potatoes preceding barley. Weed growth was significantly lower in RI barley, which received the half rate of herbicide, and CONV barley, which received the full rate of herbicide, than in BIO barley and BIO, RI, and CONV green manure, none of which received herbicide applications.

As in 1993, pest management system affected total weed growth in rotation crops in 1994 ($p<0.001$); individual contrasts (1 df) showed that weed growth in rotation crops was much lower ($p<0.01$) when herbicides were used (RI and CONV) than when they were not (BIO) (Figure 3.2d). This is consistent with the good weed control obtained in the 1993 RI and CONV pest management potatoes (Figure 3.1a). Also consistent with 1993 results, in 1994 there was no difference between RI and CONV barley (Figure 3.2d) indicating that there was no advantage to using the full rate of herbicide in these years.

Weed Density in Potatoes

The effects of pest management systems on densities of the most abundant weed species growing in potato plots are shown in Table 3.2. In 1991 through 1993 no significant differences in total weed density were observed between pest management treatments. However, significant differences in density were observed for individual species: common lambsquarters in each year, barnyardgrass and Japanese millet (treated as a single taxon because of their morphological similarity) in 1991, and low cudweed (*Gnaphalium uliginosum* L.) in 1992 and 1993 (Table 3.2). Differences in weed density between pest management treatments were not consistent from year to year. For example, density of lambsquarters was highest in the RI system in 1991, the CONV system in 1992, and the RI system in 1993 (Table 3.2).

Soil management system, i.e., rotation crop/soil amendments, had no significant effect on weed densities in potatoes except for the combined density of barnyardgrass and Japanese millet in 1992 (data not presented); density of these species was higher in amended (3.3 plants/ft^2) compared to unamended plots (1.1 plant/ft^2).

Although not significant for barnyardgrass and Japanese millet or low cudweed, in 1994 there was an interaction between pest management system and rotation crop/soil amendments that affected lambsquarters ($p=0.005$) and total weed ($p=0.005$) densities in potatoes (Table 3.2). Of particular interest was the reduction in weed density in BIO potatoes following green manure; as discussed previously (see **Weed Biomass in Potatoes**), total weed density in this treatment was equal to that measured in RI and CONV potatoes (Table 3.2).

Regression analysis was used to determine the contribution of individual weed species to total weed biomass. In 1991, 57% of the variation in total weed weight in potatoes grown in all three management systems could be predicted from knowledge of the densities of lambsquarters, barnyardgrass, and Japanese millet. In 1992, 1993, and 1994, however, there were no significant relationships between weed density and weed weight that held across pest management systems. Significant weed density-weight relationships were observed in 1992, 1993, and 1994 only for the BIO system. In 1992, 64% of the variation in total weed biomass in BIO potatoes could be explained by knowledge of the densities of barnyardgrass and Japanese millet. In 1993, 72% of the variation in total weed weight in BIO potatoes could be explained by knowledge of lambsquarters, barnyardgrass, and Japanese millet densities. In 1994, 55% of the variation in total weed shoot biomass was explained by lambsquarters density; barnyardgrass, hempnettle, or *Brassica* spp. did not account for additional variation.

Weed Density in Rotation Crops

The effects of pest management systems on densities of the most abundant weed species growing in rotation crop plots are shown in Table 3.3. No significant differences were observed between pest management treatments in total weed density in 1991 or 1992; total weed density was lower in the CONV system than the BIO and RI systems in 1993. The lower total weed density observed for the CONV system in 1993 reflected a trend ($p<0.07$) for lower density of lambsquarters in the CONV system. In 1992, lambsquarters was significantly more abundant in the RI system

Table 3.3. Pest management system effects on weed densities in rotation crops (barley and green manure). Data presented are averaged over soil management systems, which did not differ in their effects. Within each column for each year, means followed by the same lowercase letter are not significantly different.

Pest Management System	Sampling Date	Common Lambsquarters	Barnyardgrass + Japanese Millet	Low Cudweed	Total
		----------	# per sq. ft	----------	
CONV	12 July 1991	3.8 a	12.0 a	0.5 a	18.3 a
RI	12 July 1991	4.1 a	9.4 a	0.5 a	20.1 a
BIO	12 July 1991	4.4 a	11.6 a	0.4 a	18.7 a
CONV	28 July 1992	3.5 b	0.6 a	24.1 ab	30.2 a
RI	28 July 1992	12.7 a	0.7 a	15.9 b	31.4 a
BIO	28 July 1992	5.8 b	0.4 a	35.8 a	44.7 a
CONV	29 July 1993	3.7 a	1.3 a	6.5 a	15.7 b
RI	29 July 1993	8.9 a	1.6 a	8.5 a	22.6 a
BIO	29 July 1993	8.8 a	1.4 a	4.6 a	19.4 a
CONV	19 July 1994	0.8 b	0.3 a	0.1 a	2.3 b
RI	19 July 1994	2.2 b	0.5 a	0.4 a	4.5 b
BIO	19 July 1994	21.8 a	0.2 a	1.8 a	26.6 a

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

than the CONV and BIO systems. Low cudweed was significantly less abundant in the RI system than in the BIO system in 1992.

Soil management system had no effect on weed density in the rotation crop phase, with the exception of lambsquarters in 1993. Density of this weed species was higher with green manure than with barley in the CONV and RI systems, but lower with green manure than with barley in the BIO system. In 1994, lambsquarters and total weed densities were significantly lower in the RI and CONV pest management systems than in the BIO system (Table 3.3), which was probably the result of very good weed control in the 1993 RI and CONV potatoes (see Figure 3.1a).

In 1991, no significant relationship was detected between weed density and total weed biomass in the rotation crop phase of any of the pest management systems. In contrast, across pest management systems in 1992, 67% of the variation in total weed biomass production could be explained by variations in density of lambsquarters. In 1993, 39% of the variation in total weed biomass could be explained by knowledge of lambsquarters, barnyardgrass, and Japanese millet densities. In the 1994 rotation crops, densities of lambsquarters, hempnettle, and low cudweed explained 84% of the variation measured in total weed biomass. Thus, numerically abundant weeds produced the majority of weed biomass in rotation crops.

Weed Seed Density

In 1994, the community of germinable weed seeds in the surface 4 in. of soil was dominated by low cudweed and lambsquarters. The total number of germinable seeds summed over all weed species was affected by a three-way interaction between pest management system, phase of the rotation sequence, and soil management system (Table 3.4). The three-way interaction was also observed for germinable lambsquarters seeds, but not for barnyardgrass or low cudweed. Not surprisingly, weed seed abundance was lowest in plots following CONV potatoes or barley. Total germinable seeds were highest following green manure used as a rotation crop in the RI and CONV pest management systems. In these systems germinable seeds were comparatively lower following barley, presumably reflecting the efficacy of the herbicide application in the RI and CONV barley.

Because of the longevity of seeds of many weed species, the seedbank is considered an indicator of the long-term success of a weed management system. To assess the change in the seed bank from 1991 to 1994, the difference in germinable seeds (1994 minus 1991) was analyzed. A positive value thus indicates an increase, zero indicates no change, and a negative value indicates a decrease in the seedbank. The total density of germinable seeds summed over all species increased over the four years in all pest management systems, with the smallest increase in the CONV system and interestingly, the largest increase in the RI system (Figure 3.3).

The increased weed seed density in the RI system is due primarily to an increase in low cudweed. Low cudweed was not affected by pest management system in 1991 and thus is not artificially inflated in the RI system (data not presented). The reason for the increase in low cudweed is not known, but could be related to the unusually high density observed in the 1992 RI potatoes (Table 3.2).

Lambsquarters seed density increased in all pest management systems, while the barnyardgrass + Japanese millet combination

Table 3.4. Pest management system, soil management system, and phase effects on densities of germinable weed seeds in soil samples collected on 3–4 June 1994. Within each column, means followed by the same lowercase letter are not significantly different.

Pest Mgt. System	Soil Mgt. System	Phase 1993 Crop	Common Lambs-quarters	Barnyard-grass + Japanese Millet	Low Cudweed	Total
			# per sq. ft			
CONV	(-)	barley	73 ef	7 bcd	102 c	226 e
	(+)	GM	424 a	23 ab	409 ab	906 ab
	(-)	potato	18 f	8 bcd	151 bc	221 e
	(+)	potato	29 f	4 bcd	289 bc	376 de
RI	(-)	barley	214 bcde	7 bcd	314 bc	628 bcd
	(+)	GM	299 abcd	12 bcd	649 a	1035 a
	(-)	potato	164 cde	5 bcd	418 ab	663 bcd
	(+)	potato	115 def	8 bcd	284 bc	468 de
BIO	(-)	barley	385 ab	27 a	220 bc	688 abcd
	(+)	GM	213 abcde	20 abc	281 bc	637 abcd
	(-)	potato	203 abcde	0 d	197 bc	488 cde
	(+)	potato	338 abc	3 cd	367 ab	764 abc
ANOVA						
Pest Management System (PM)			p=0.027	p=0.809	p=0.130	p=0.094
Phase (P)			p<0.010	p<0.010	p=0.639	p<0.010
Soil Management System (SM)			p=0.116	p=0.903	p<0.010	p<0.010
interactions						
PM*P			p=0.013	p=0.019	p=0.280	p=0.143
PM*SM			p=0.052	p=0.868	p=0.643	p<0.010
P*SM			p=0.346	p=0.841	p=0.136	p=0.013
PM*P*SM			p<0.010	p=0.131	p=0.084	p<0.010

CONV = conventional, RI = reduced input, and BIO = biological pest management systems.
GM = green manure, a mixture of pea, oat, and hairy vetch.
(-) = without compost and manure amendments.
(+) = with compost and manure amendments.

decreased from 1991 to 1994 (Figure 3.3). Despite the general increase in the weed seedbank (Figure 3.3), there has not been a dramatic increase in weed density or biomass in potatoes (Table 3.2 and Figure 3.1). Either the measured seedbank increase is insufficient to cause an increase in weed density, or mortality factors,

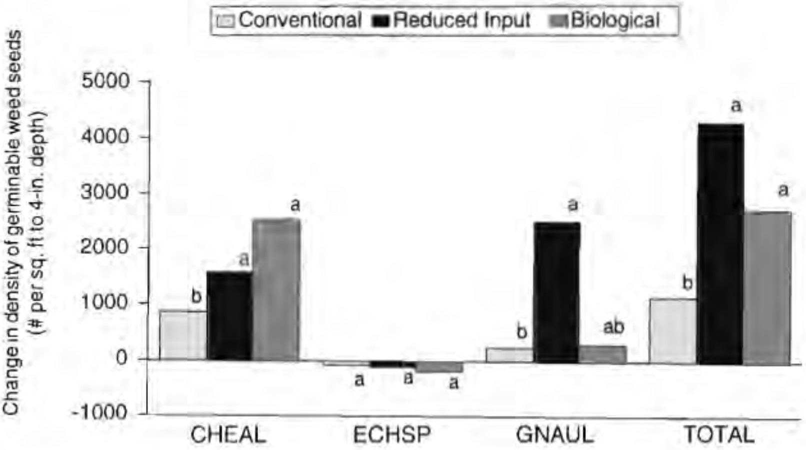


Figure 3.3. Pest management system effects on the change in densities of germinable weed seeds. Data are number of seeds in 1994 minus the number of seeds originally found in 1991 and are averaged over phase and soil management system which, except for phase affecting lambsquarters (see text), were not significant effects.
CHEAL = common lambsquarters; ECHSP = Japanese millet + barnyardgrass; GNAUL = low cudweed; TOTAL = sum of all weed species.

natural or a result of the pest and soil management systems, keep the germinable seeds from successfully establishing.

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The 1994 field season completed the fourth year of studying weed dynamics in the Atlantic potatoes and their associated rotation crops. Over this period, effects of pest and soil management systems on weed dynamics have been quantified by measurements of weed density, biomass, and seed density.

Weeds have been well managed over the two rotation cycles completed to date. Weed biomass, which is an indicator of resources preempted from associated crops and thus a measure of weed management success, was quite low in all treatment combinations in all four years: less than 250 lbs/A in potatoes (Figure 3.1) and less than 335 lbs/A in the rotation crops (Figure 3.2). Potato yield, also an indicator of weed management success, was not related—based on analysis of covariance—to weed density or biomass. Although this suggests that weed interference has been minimal, the definitive data are not yet available, but will be generated in future years by comparing yields to weed-free subplots. The major factors driving weed dynamics in this agroecosystem—crop rotation, herbicides, cultivation, and crop competition—have, in some instances, generated distinct effects on the weed community.

Soil management has had major impacts on weed dynamics. Weed biomass in BIO potatoes grown in the amended soil management system was lower than in the unamended system (Figure 3.1b) despite similar amounts of weed biomass produced in the previous rotation crops (Figure 3.2c) and similar seedbank densities at the start of the season (Table 3.4). Whether the result of allelochemicals, increased cultivation efficacy, increased crop competition or decreased weed competition, or another mechanism related to the biological intensity of this system, this reduction in weed biomass during the potato phase could improve the overall performance of the BIO system in which green manure and soil amendments are used. While weed control options are somewhat limited in the green manure rotation crop, postemergence cultivation will be used in 1995 to increase weed control in the BIO barley.

The influence of herbicides on weed dynamics has had dramatic effects. In the CONV and RI systems, which include herbicides, weed biomass measured in 1993 and 1994 was very low compared to the BIO system (Figures 3.1a and b). Of particular interest in reference to economic and environmental concerns is the similarity between these two herbicide-based systems. Although the RI system receives one-half the amount of herbicide that the CONV system receives (Table 3.1), weed control in the RI potatoes in 1993 and 1994, and RI barley in 1994, was equal to the corresponding CONV systems (Figures 3.1 and 3.2d). Increasingly there is interest in reducing herbicide use in weed management systems; a logical place to start is by reducing rates.

The weed seedbank, perhaps a better indicator of long-term progress of weed management than weed biomass and potato yield, has experienced a net increase in total weeds (Figure 3.3). This increase is deceiving, however, because the dominant weed species in the agroecosystem (low cudweed, common lambsquarters, and barnyardgrass + Japanese millet) demonstrate unique patterns of seedbank population dynamics. While low cudweed has shown a net increase in the seedbank (Figure 3.3), individually, some treatments have an oscillating pattern of density while other treatments appear to be at an equilibrium density (data not presented). Low cudweed thus demonstrates a pattern of persistence in the seedbank. In contrast, barnyardgrass + Japanese millet density in the seedbank has decreased to the point where it was not detected in certain plots in 1994. A third pattern, in contrast to both the persistent low cudweed and the declining barnyardgrass + Japanese millet, is exhibited by common lambsquarters, which has increased in the seedbank (Figure 3.3). The increase in lambsquarters seeds is cause for particular concern in the RI and BIO systems. It remains to be seen whether the integrated systems driving weed dynamics in these plots will keep this species at levels that do not interfere with yields.

IV. Insect Pests and Natural Enemies

Francis A. Drummond and Eleanor Groden

INTRODUCTION

The most destructive insect pest of table stock potatoes in Maine is the Colorado potato beetle (CPB), (*Leptinotarsa decemlineata* (Say)). This insect usually completes one generation per year in northern Maine, but occasionally it completes a partial second generation. Because of its ability to increase 100-fold per generation (May 1986) and its propensity to develop resistance to most of the insecticides used to control it (Roush and Tingey 1993), the potato beetle has been the focus of most insect pest management programs for potatoes. There are also three common aphid pests of potato in northern Maine: the green peach aphid (*Myzus persicae* (Sulzer)); the potato aphid (*Macrosiphum euphorbiae* Thomas); and the buckthorn aphid (*Aphis nasturtii* Khaltenbach). The green peach aphid is considered the most serious aphid pest in Maine potato production due to its efficiency as a vector of potato viruses. In seed potato production, the economic threshold for green peach aphid is a single winged adult.

Beneficial insects monitored during the first four years of this research project were the following insect generalist predators: ground beetles, spiders, ladybeetles, and the asopine stinkbug (*Podisus maculiventris*). While ladybeetles are usually considered generalist predators, in northern Maine potato ecosystems their dynamics are intimately associated with specific potato-infesting and small-grain-infesting aphids.

The insect community is an indicator of the functioning of the potato ecosystem. Increases in pest populations point to management practices that may not be sustainable. Increases in beneficial insect populations, on the other hand, with an accompanying decrease in pest populations indicate more sustainable agricultural systems. It was with this philosophical viewpoint that the analysis of the pest management, soil management, and variety treatments on insects was conducted.

METHODS

All potato plots were sampled twice per week in 1991 and once per week in 1992, 1993, and 1994, throughout the growing season. In 1991 and 1992, 50 random plants per plot were examined initially. As plants increased in size, samples were reduced to 30 plants per plot. In 1993 and 1994, 30 plants per plot were sampled initially, and the number was reduced to 20 per plot during August. The densities of CPB adults, egg masses, small (first and second instars) and large larvae (third and fourth instars), potato flea beetle (*Epitrix cucumeris* (Harris)) adults and damage, green peach aphid, spiders, and the stinkbug predator were recorded per plant in all years. In 1991, densities of ladybeetles and aphids other than green peach were recorded; in 1992 through 1994, potato aphid, buckthorn aphid, and all ladybeetles were identified and recorded by species. CPB and aphid densities were summarized weekly to determine if economic thresholds for these pests were exceeded and if insecticide treatments were necessary (see Appendix B for more detail). Seasonal densities or seasonal incidence of insects were estimated for each plot by integration of the insect-count time series (Groden 1989). Additionally, randomized complete block split plot design analyses of variances were used to determine if pest management and soil fertility management systems had significant impacts on these insect populations. Treatment means were separated statistically using Fisher's Least Significant Difference test. Relationships between seasonal densities of CPB and crop yields were examined using regression.

Ground-dwelling carabid populations were sampled twice during the growing season in 1991 (30 June–6 July and 12–18 August) and 1992 (26 June–1 July and 16–22 August). Five pitfall traps (1/2 liter plastic containers) half filled with a 1:1 ethylene glycol and water solution were randomly placed and dug into each of 48 plots (barley and paired Superior potato plots). The average number of carabid beetles caught in each pitfall trap per plot was used as the dependent variable in the randomized complete block split-plot design analyses of variances to assess the impact of the three pest management systems and the two soil management systems on the natural carabid community.

RESULTS AND DISCUSSION

Pest Management Systems

In 1991 conventional (CONV) plots exceeded the economic threshold for CPB, requiring insecticide applications twice throughout the growing season, while the reduced input (RI) plots required one application of *Bacillus thuringensis* (*Bt*) (Table 4.1). In 1992 through 1994, CONV plots exceeded the economic threshold more frequently, requiring more foliar applications for CPB than the BIO plots. The addition of predator releases in the BIO plots in 1993 and 1994 reduced the need for foliar applications of *Bt*/*B. bassiana*

Table 4.1. Insect pest management practices used for control of the Colorado potato beetle and the aphid complex on potato.

	Treatment and Number of Applications[1]			
	1991	1992	1993	1994
Colorado potato beetle				
BIO	—	Bt/Bb[3]	Bt/Bb[3]	Bt/Bb[4]
		1.25	1.00	2.0
		rotenone[5]	predator release[6]	predator release
		0.75	3.0	3.0
RI	Bt[2]	esfenvalerate	esfenvalerate	esfenvalerate
	1	1.25	1.25	2.00
	rotenone[5]			
	0.25			
CONV	esfenvalerate[7]	esfenvalerate	esfenvalerate	esfenvalerate
	1	2.25	2.75	3.00
	endosulfan[8]			
	1			
Aphids				
BIO	—	pyrethrum[10]	pyrethrum[10]	pyrethrum[10]
		1.00	5.25	5.25
RI	pyrethrum[9]	methamidophos[11]	methamidophos	methamidophos
	3	0.50	0.25	1.0
CONV	methamidophos	methamidophos	methamidophos	methamidophos
	1	1.50	0.25	1.0

[1] In 1991 decisions for applying insecticides were based upon pest densities averaged over four blocks, therefore, all plots within a given pest management system received the same number of insecticide applications. In 1992, 1993, and 1994, decisions were based on pest densities averaged within a block, therefore, each block received insecticide treatments as needed. Numbers presented for 1992–1994 represent the mean number of applications over the four blocks for each pest management system.

[2] Foil®, rate = 5 qst/A.

[3] Foil®, rate = 5 qts/A mixed with *Beauveria bassiana* (RS252 strain), rate = 5x10^{13} conidia/ha.

[4] Foil®, rate = 3 qts/A mixed with *Beauveria bassiana* (RS252 strain), rate = 5x10^{13} conidia/ha.

[5] Rotacide® 5EC, rate = 2.7 qts/A.

[6] Released 1.0 *Perillus bioculatus* predator nymph/plant

[7] Asana® XL.66EC, rate = 9.0–9.6 oz/A + peperonyl butoxide (pbo), rate = 4.0 oz/A.

[8] Thiodan® 3EC, rate = ¾ qt/A.

[9] Agway Organic Spray® (1% pyrethrum), rate = 11.6–13.3 oz/A.

[10] Pyrenone®, rate = 12 oz/A.

[11] Monitor® 4, rate = 1–2 pts/A.

and rotenone to an average of once per season in 1993 and twice per season in 1994. For 1992 through 1994, the reduced input (RI) plots required fewer foliar insecticide applications to maintain beetle populations below threshold compared with the CONV plots. The economic thresholds in these plots, however, were double the number of insects tolerated in the CONV plots. The RI plots required fewer applications than the BIO plots in 1992. However, in both 1993 and 1994, even with the lower thresholds in the BIO plots, more foliar applications to control CPB were required in the RI compared with the BIO treatment.

Aphids exceeded economic thresholds and required foliar applications of insecticides more frequently in the BIO plots than the CONV and the RI plots in all years except 1992 (there was no biological pes management system in 1991). In 1992, CONV plots required more foliar applications for aphids than either the BIO or RI treatments. In 1993, however, both the CONV and RI plots averaged only 0.25 insecticide applications per plot for aphids, while the BIO plots required an average of 5.25 applications.

Colorado Potato Beetle

Pest management systems did not significantly affect seasonal densities of CPB in 1991 and 1992 (Figures 4.1 and 4.2), indicating that all strategies were equivalent in reducing CPB densities. In 1993, however, there were significantly fewer CPB small and large larvae and summer (second generation) adults in the BIO. In 1994, there were fewer of all CPB life stages (first generation adults, egg masses, small and large larvae, and summer adults) in the BIO plots compared with the CONV and RI plots. Since 1992, the densities of CPB in the BIO plots have been declining relative to the other two treatments (Figure 4.3), indicating a possible between-year effect of pest management systems on CPB densities.

Regression analysis was used to examine the relationship between the density of summer adults produced in each plot in one year to the density of spring colonizing (prespray) adults in the adjacent (rotated) plot the following year. A significant linear relationship was revealed for both 1992 to 1993 and 1993 to 1994 (Figure 4.4), with 40% and 22%, respectively, of the variation in current year colonizing adults explained by the density of adults produced the previous season. Given the layout of plots in this study, it is likely that many beetles produced as a result of different pest management systems overwinter at the same location in field borders and redistribute themselves between treatments the following spring. That there is a significant relationship between beetles produced in a plot and colonizing beetles the following spring indicates that a portion of the population likely overwinters in the field. In a larger-scale farming operation, without the redistribution of overwintered beetles from field borders that were actually produced in neighboring treatments, we would expect the between-year decline in beetles to be greater with the BIO pest management system.

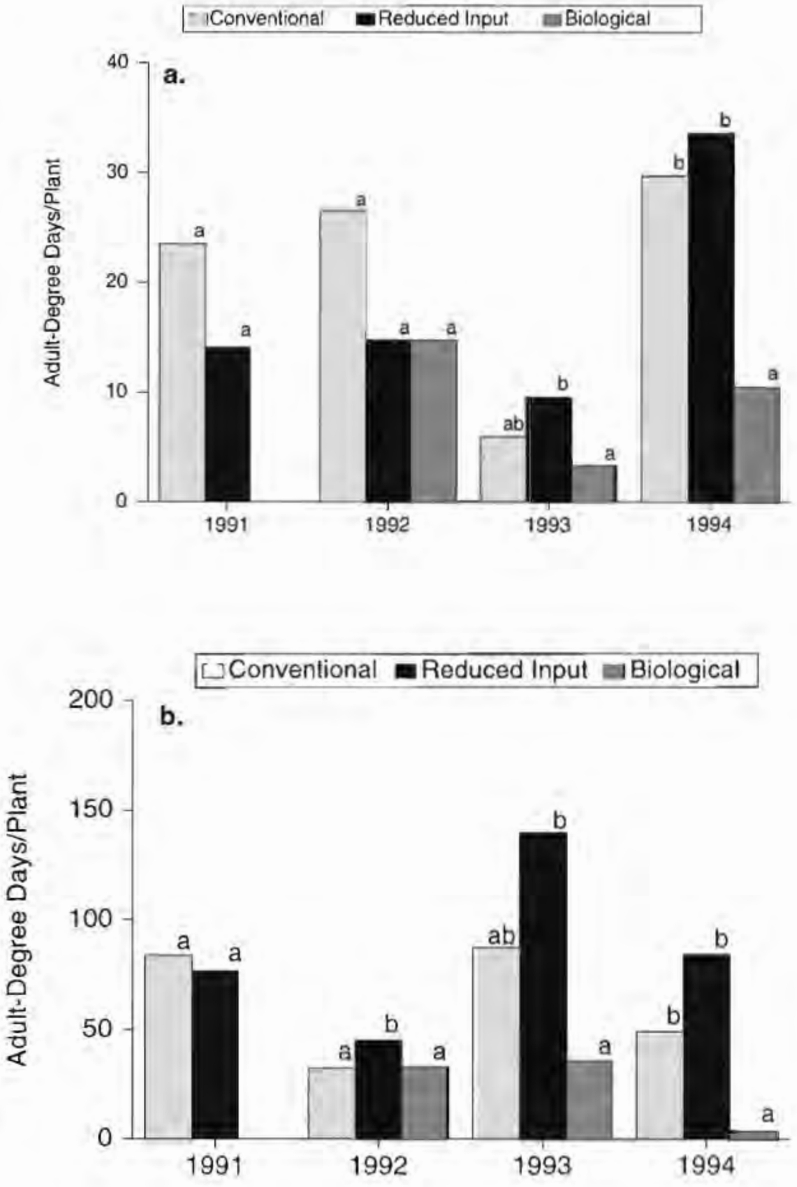


Figure 4.1. The incidence of first (overwintered) (a) and second (summer) generation (b) CPB adults in the different pest management systems in 1991–1994. Columns with the same letter indicate no significant differences between treatments within that year. There was not a biological pest management system in 1991.

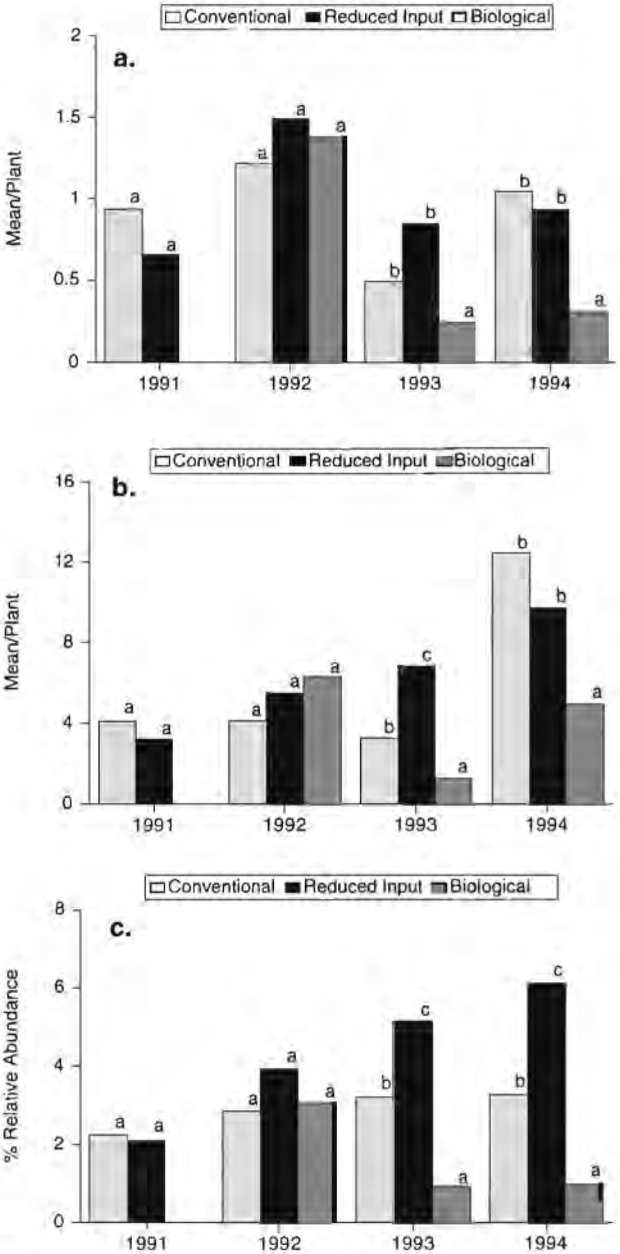


Figure 4.2. The seasonal densities of CPB egg masses (a), small larvae (b), and large larvae (c) in the different pest management systems in 1991–1994. Columns with the same letter indicate no significant differences between treatments within that year. There was not a biological pest management system in 1991.

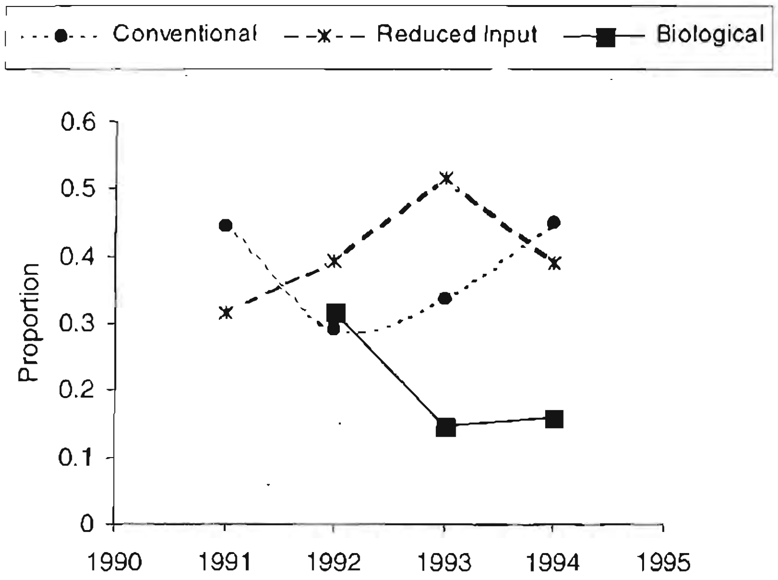


Figure 4.3. The proportion of colonizing (prespray) CPB adults in the different pest management systems from 1991–1994.

Seasonal densities of CPB did not differ between the two potato varieties, Atlantic and Superior, in 1992 and 1993. In 1991, however, there were significantly more adults, eggs, and large larvae on the Atlantic plants than the Superior plants, and this difference was also seen for first generation adults in 1994. Compost and manure amendments did not affect densities of any CPB life stages from 1991 through 1993, except for lower egg densities in 1992 in the unamended plots compared with the amended plots. In 1994 there was a significant amendment effect on seasonal densities of all CPB life stages and a significant interaction between amendment and variety on the seasonal densities of first generation CPB adults and egg masses. CPB densities were lower on the amended Atlantic plots compared with the unamended Atlantic plots, but were equally low in both the amended and the unamended Superior plots (Figure 4.5). It is unclear why CPB densities were higher on the Atlantic plots than the Superior plots in 1991 but not in subsequent years. Aroostook County experienced a severe drought in 1991. It is possible that the relative attractiveness to beetles of these two varieties is affected by water stress. Delayed planting of

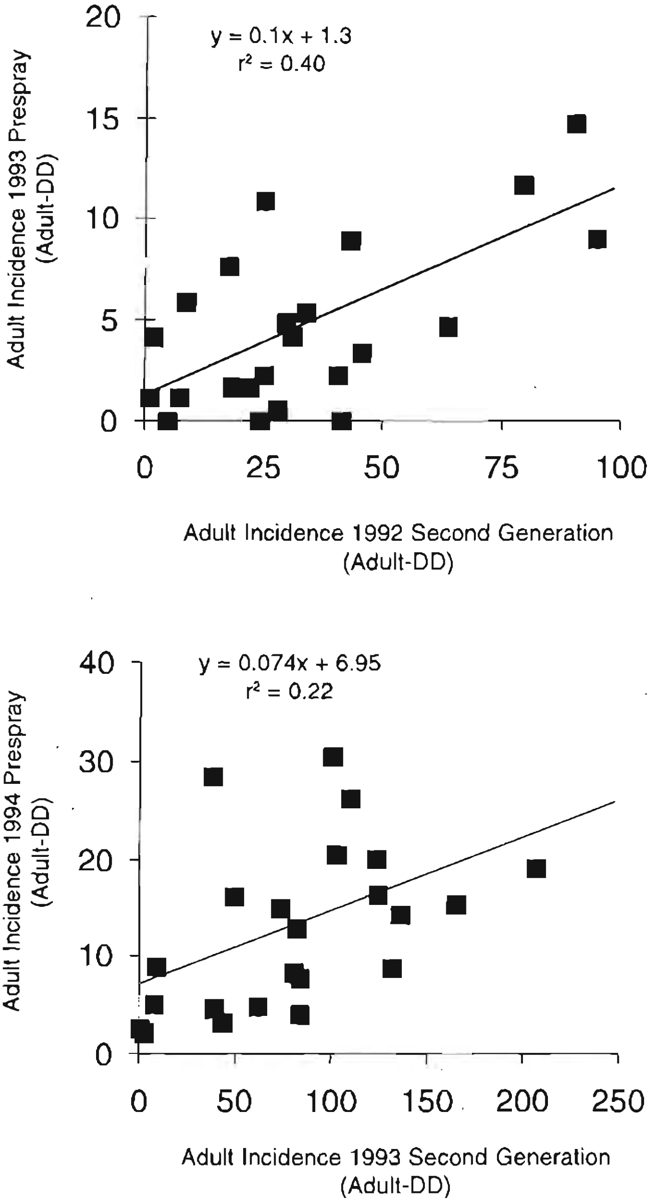


Figure 4.4. The relationship between beetles produced in a plot in one year to the density of beetles colonizing the adjacent plot the following year. The top graph is the incidence of 1992 summer (generation 2) adults plotted vs the incidence of adults in spring 1993 before any insecticide treatments. The bottom graph show the same data for 1993 to 1994.

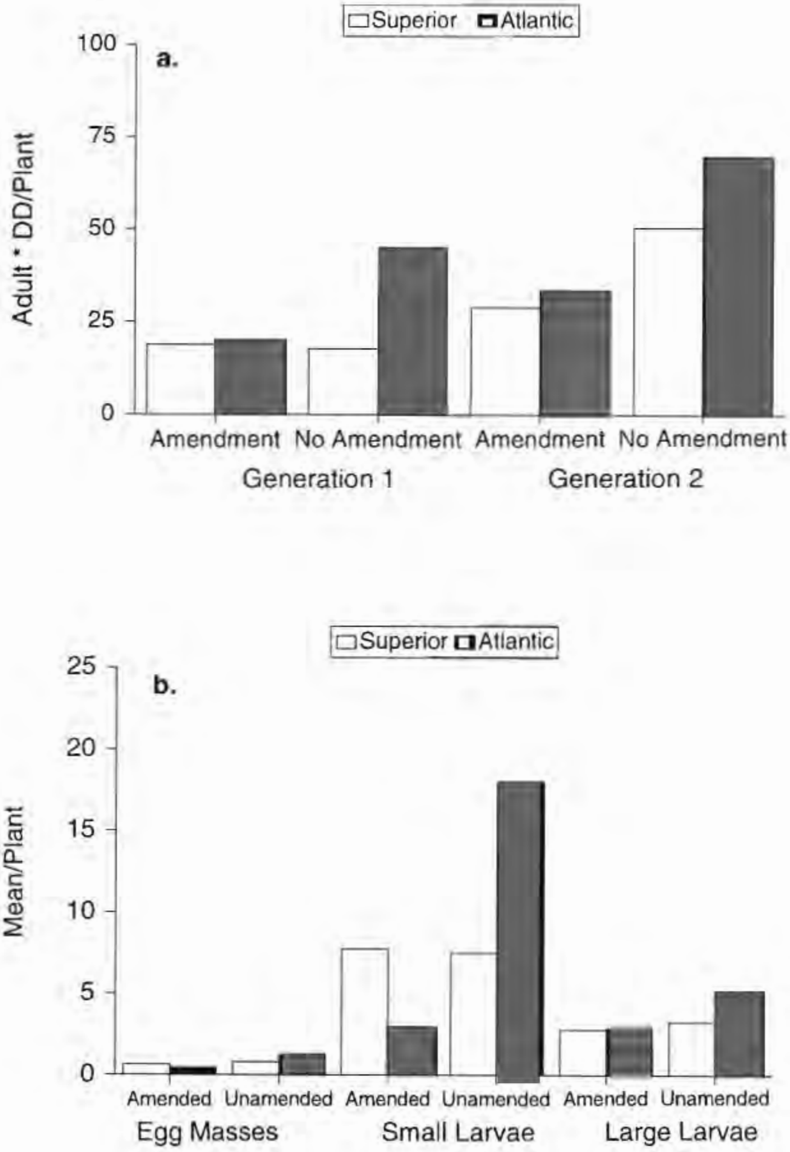


Figure 4.5. Seasonal incidence of CPB adults (a) and seasonal densities of immature life stages (b) in amended and unamended Superior and Atlantic plots in 1994.

the amended Atlantic plots and poor quality seed for the Superior plots in 1994, resulted in larger, more vigorous plants in the unamended Atlantic plots compared with the other plots at the time of colonization by spring CPB adults. Prespray adult densities were significantly higher in the unamended Atlantic plots, and this resulted in more CPB eggs and subsequently higher larval densities. These differences are most evident in the early season. Successful management of CPB populations reduced the variety and amendment differences over time.

Potato Flea Beetle

From 1991 through 1994 the potato flea beetle was the dominant species of flea beetle sampled in the potato plots. Variegated flea beetle and eggplant flea beetle were not commonly found. Potato flea beetle is usually not a significant pest in northern Maine, therefore, specific tactics were not implemented for its control. Flea beetle populations occurred at fairly constant densities between years (mean = 2.1/plant in 1991, 1.6/plant in 1992, 1.5/plant in 1993, and 2.6/plant in 1994), and in three of the four years (1992–1994), pest management systems significantly affected potato flea beetle densities. There was a significant interaction between soil amendments and pest management systems ($p<0.05$, Figure 4.6). Flea beetle numbers were lower in unamended plots compared to amended plots in the BIO treatments. There was no significant effect of soil amendments in the RI or CONV plots. The greater number of foliar insecticides used for control of CPB adults in the CONV compared to the BIO plots likely reduced flea beetle populations in the CONV plots. The impact of soil amendments on flea beetle densities is more difficult to discern. Flea beetle adults lay their eggs in the soil, and the larvae feed on the root hairs of the potato plant. The addition of manure and potato compost to the soils just before planting in the spring may have enhanced the attractiveness of these plots to adults for oviposition.

Aphids

In 1991, aphids were recorded as either "green peach" or "other" aphid species; therefore, the most abundant aphid species cannot be determined. The most abundant aphid species found infesting potato in 1992 was the potato aphid, while in 1993 and 1994, the buckthorn aphid was the most abundant aphid species (Figure 4.7). In 1994, green peach aphid constituted ca. 30.7% of the aphid pest community on potato, whereas in the three previous

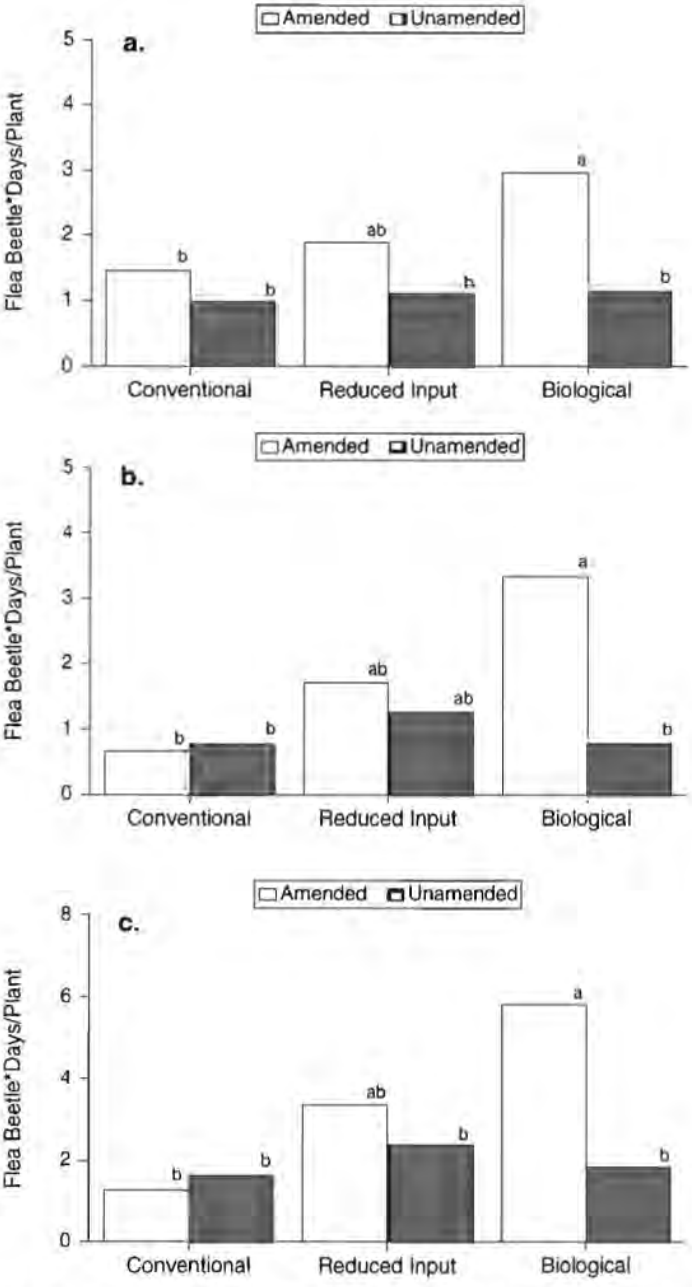


Figure 4.6. Incidence of adult potato flea beetles in 1992 (a), 1993 (b), and 1994 (c) as influenced by pest management and soil management systems. Bars with the same letter (within a year) are not significantly different (p = 0.05).

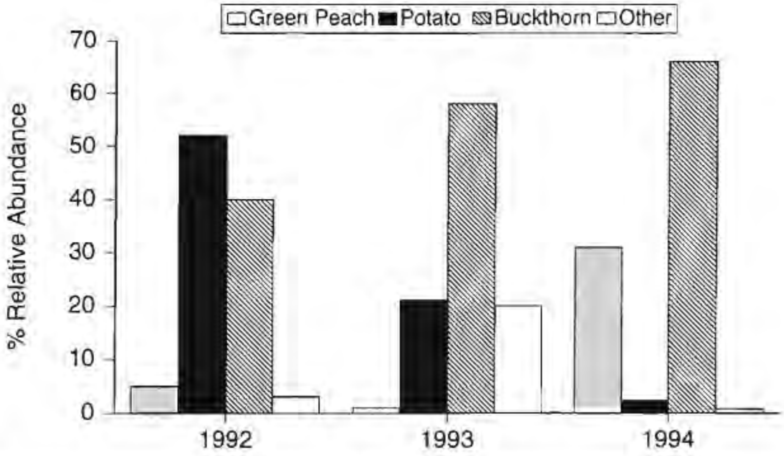


Figure 4.7. Relative abundance of the major aphid pest species of potato, 1992–1994.

years, green peach aphid ranged between 1.2% and 7.6% (1993 and 1991, respectively) of the total aphid abundance on potato.

Green peach aphid densities were not consistently affected by soil management, variety, or pest management over the four years of the study. The only effects we observed due to pest management were in 1991, where a significant ($p=0.05$) interaction between pest management and variety was observed and in 1994 where a significant ($p=0.009$) pest management effect was present. In 1991 green peach aphid densities were significantly greater in the CONV plots compared to the RI plots, but only in those plots planted to Atlantic. There were no significant differences in green peach aphid densities due to pest management in plots that were planted to Superior (Figure 4.8a). The Atlantic plots were planted seven days later than the Superior plots in 1991. The phenological difference in the two varieties due to planting date may have affected aphid colonization and, thus, differences in abundance and, possibly, efficiency of control. The following three years provided no additional evidence to suggest that this variety-pest management interaction is characteristic of the cropping system. In 1994, green peach aphid densities were greater in the BIO plots than either the CONV or RI plots (Figure 4.8b). Apart from 1994, however, the abundance of green peach aphids was extremely low compared to the other aphid species infesting potato.

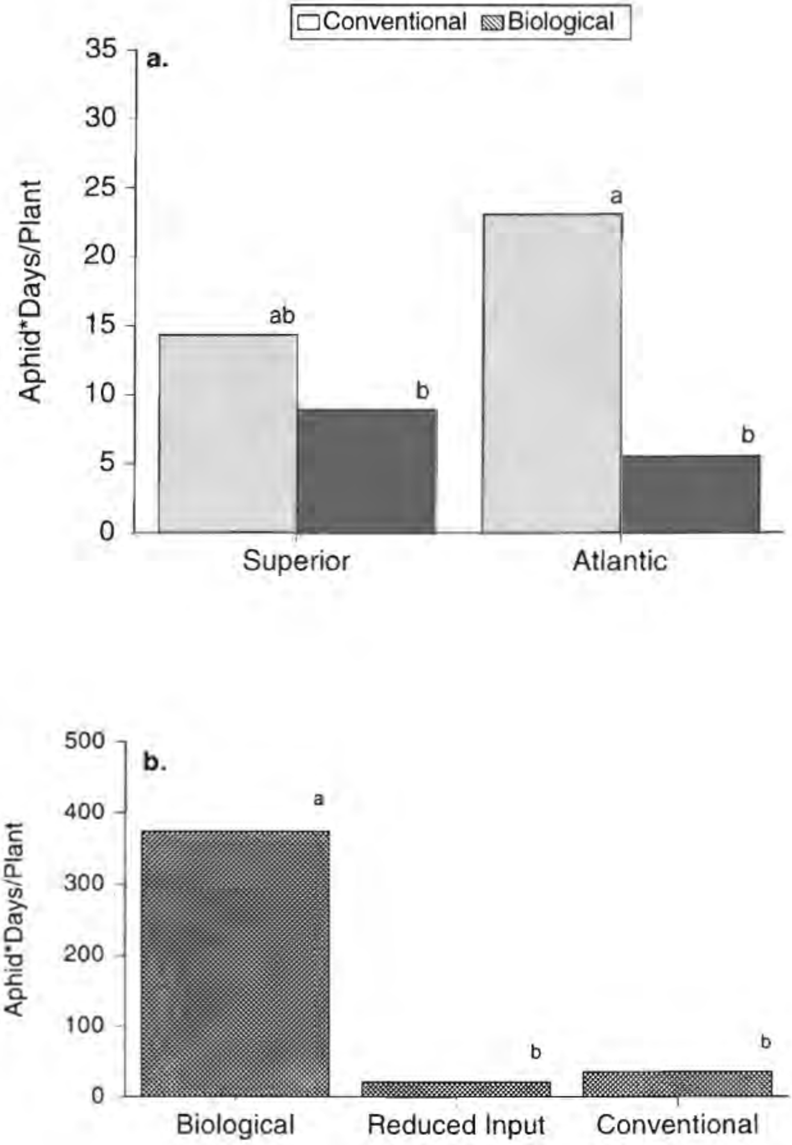


Figure 4.8. Effects of potato variety and pest management on green peach aphid incidence in 1991 (a) and of pest management in 1994 (b). Bars with the same letters (within a year) are not significantly different (p<0.05).

Potato aphid abundance was significantly affected by both pest management and variety in 1993 and 1994 (Figure 4.9a). In both these years, potato aphid abundance was higher in the BIO plots than the RI or CONV plots, which were not significantly different from each other. A similar (not significant at $p<0.05$) trend toward higher potato aphid abundance in the BIO plots compared to the RI and CONV plots was observed in 1992 (Figure 4.9a). In 1993, potato aphids were more abundant on Superior than on Atlantic, whereas in 1994, Atlantic was more heavily infested (Figure 4.9b). A significant ($p=0.04$) variety × soil amendment interaction was observed in 1993. A trend of higher potato aphid densities in unamended plots was observed. This difference was highly significant in the Superior plots (mean = 323.2 ± 57.7 aphid*days/plant, unamended; mean = 187.4 ± 45.3 aphid*days/plant, amended), but less pronounced in the Atlantic plots (mean = 156.1 ± 15.3 aphid*days/plant, unamended; mean = 123.8 ± 17.2 aphid*days/plant, amended). This was the only year, however, that the soil amendment treatment had an effect on potato aphid abundance; the amendment effect was not observed with the other aphid species. This effect is probably due to an indirect effect of soil amendment on potato plant nutrition modified by potato variety.

Both variety and pest management system significantly affected buckthorn aphid abundance in 1992, 1993, and 1994. The effect in all three years was due to an interaction between variety and pest management system ($p=0.02$, $p=0.02$, and $p=0.03$; 1992-1994, respectively). In 1992, buckthorn aphids were least abundant in Atlantic potatoes receiving the RI and CONV pest management systems. Their abundance did not differ between varieties in the BIO pest management system, and BIO treatments were not significantly different from the Superior/RI or Superior/CONV treatment combinations (Figure 4.10a). Buckthorn aphid abundance in 1993 was higher in the BIO treatment compared to the RI and CONV treatments. Within the BIO plots, potato variety again did not affect abundance (Figure 4.10b). Abundance was not significantly different between RI and CONV treatments, but within these two pest management systems, Atlantic potatoes had a lower abundance of buckthorn aphids than Superior potatoes. Buckthorn aphid abundance in 1994 was highest in the BIO treatment compared to the RI and CONV treatments. In the BIO and CONV treatments, however, Superior plots supported a higher density of buckthorn aphids than the Atlantic plots. In the RI plots the difference was not significant (Figure 4.10c). Over the three years, the general pattern of buckthorn aphid abundance was that

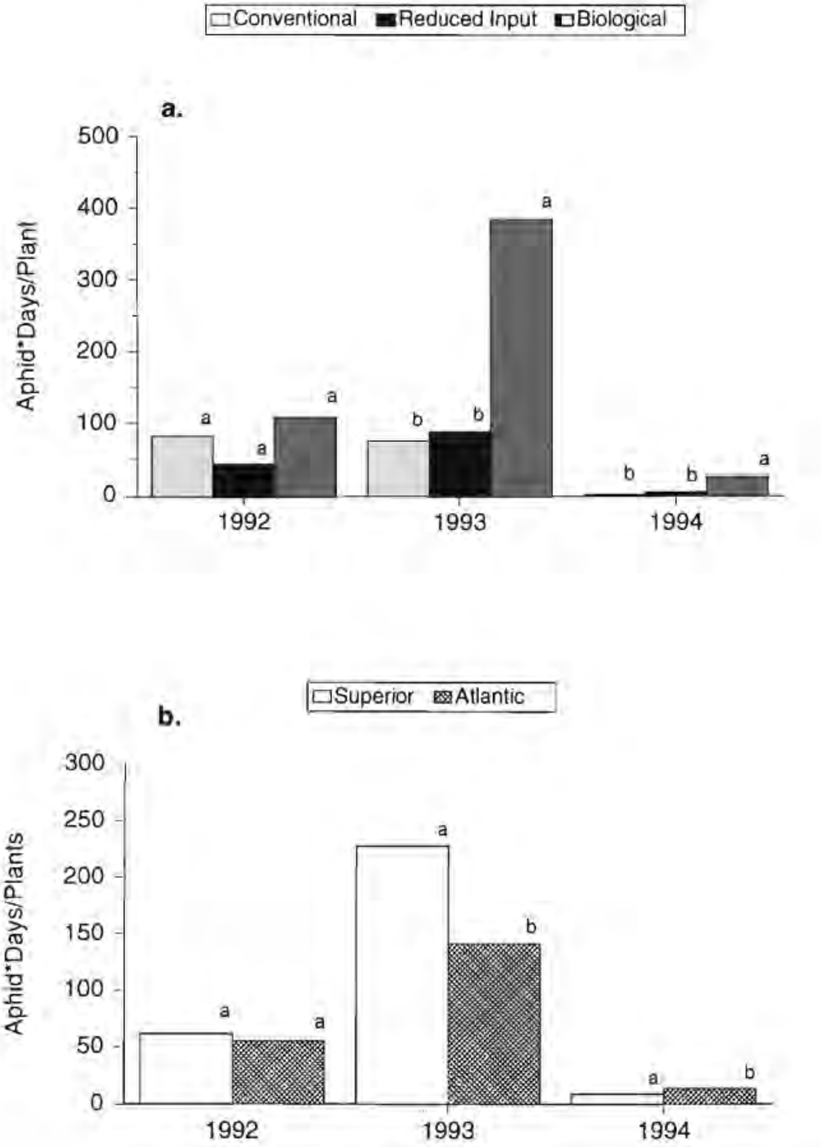


Figure 4.9. Effects of pest management treatment (a) and potato variety (b) on incidence of potato aphid, 1992–1994. Bars with the same letter (within a year) are not significantly different (p<0.05).

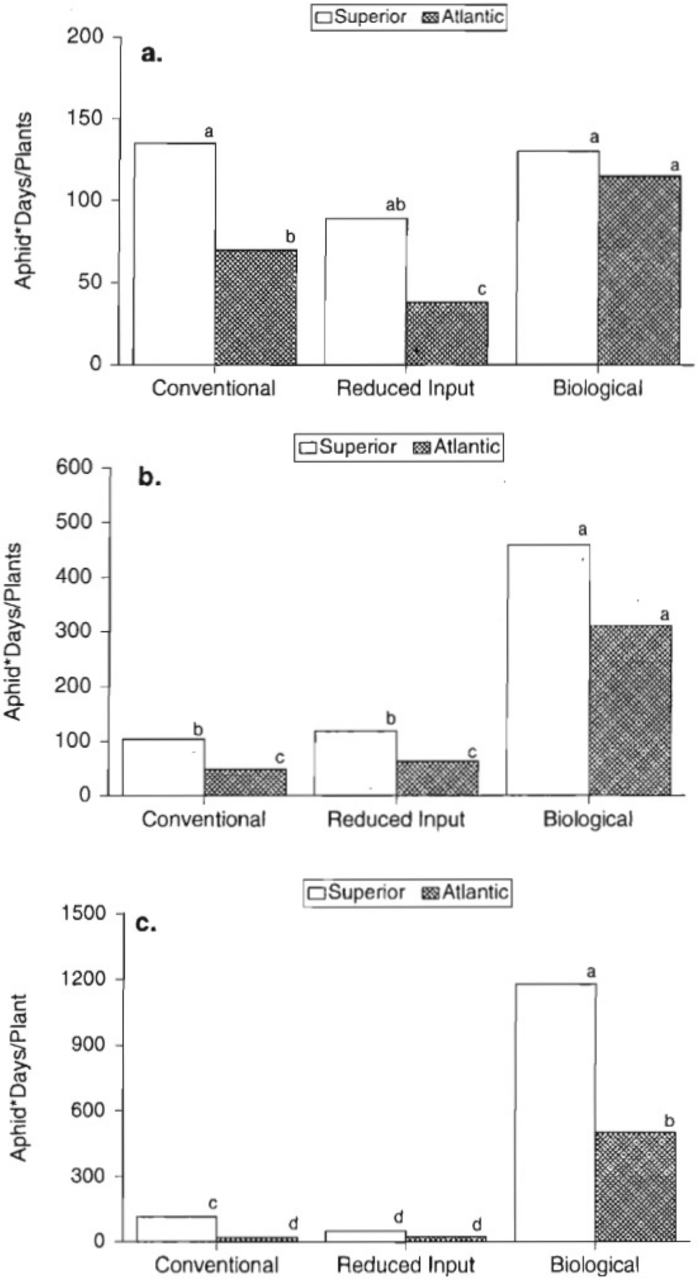


Figure 10. Effects of pest management system and potato variety on buckthorn aphid incidence in 1992 (a), 1993 (b), and 1994 (c). Bars with the same letter (within a year) are not significantly different ($p<0.05$).

it was higher in the BIO treatment than the RI or CONV treatment, and in general, Superior supported higher densities of buckthorn aphids than Atlantic. Soil amendment treatment effects were not observed on buckthorn aphid density.

"Other" aphids were those aphids that could not be easily identified in the field by the pest management scouts. These included various species of grain-infesting aphids blown into the potato plots and the potato-infesting melon aphid. Because this grouping of aphids might not have been the same mixture of species from year to year, it might not be expected that consistent treatment differences would be detected. The following effects (Figure 4.11) on "other" aphid abundance were measured: in 1991, a pest management × variety interaction ($p=0.01$); in 1992 a variety effect ($p=0.005$) and a trend in pest management ($p=0.07$); in 1993 a trend in variety ($p=0.07$); and in 1994 a pest management effect ($p=0.04$). In 1991 "other" aphid abundance was significantly higher in the CONV/Superior treatment combination compared to the other three treatments (Figure 4.11a). There were no differences in abundance due to variety within the RI treatment. In 1994, there were significantly more "other" aphids in the BIO treatment than in the CONV or RI treatment, which were not significantly different from each other (Figure 4.11b). A similar trend of higher densities of "other" aphids in the BIO treatment compared to the RI and CONV treatments was also observed in 1992, although as stated earlier this trend was not significant at $p\leq0.05$ (Figure 4.11b). Potato variety significantly affected "other" aphid abundance in 1992, with higher densities observed in Superior compared to Atlantic (Figure 4.11c). A similar trend ($p=0.07$) in abundance appeared in 1993 (Figure 4.11c). In summarizing these findings, there is evidence to suggest a somewhat consistent effect of pest management system on "other" aphid abundance (with higher densities being found in plots receiving BIO treatment compared to plots receiving RI and CONV treatments); and we have found evidence to suggest there is a tendency for Superior to support higher densities of "other" aphids than Atlantic.

In addition to assessing the effect of variety, pest management, and soil amendment treatments on individual aphid species, we also investigated the effect of these experimental treatments on the total numbers of aphids regardless of the species. We found no evidence to suggest that soil amendment was affecting the total abundance of aphids. Pest management system and variety, however, did significantly affect total aphid numbers (Figure 4.12). An interaction between pest management system and variety existed

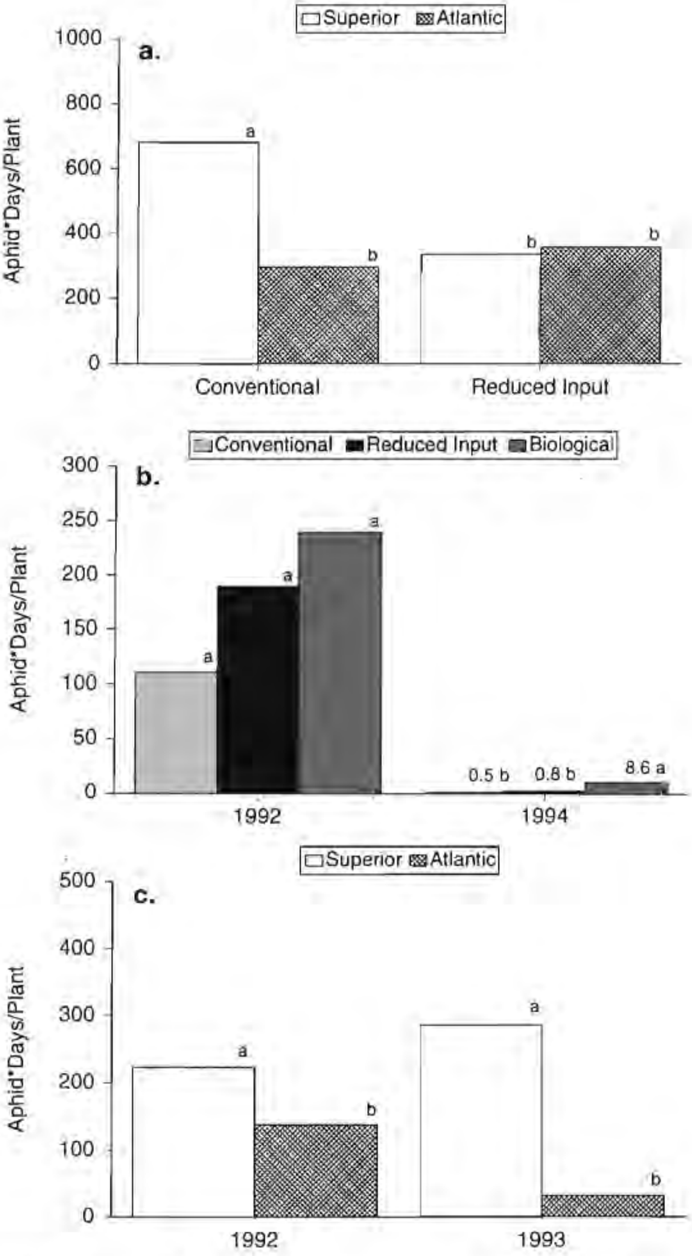


Figure 4.11. Effects of potato variety and pest management system interactions on "other aphid" incidence in 1991 (a), pest management system on "other aphid" incidence in 1992 and 1994 (b), and variety on "other aphid" incidence in 1992 and 1993 (c). Bars with the same letter (within a year) are not significantly different (p<0.05).

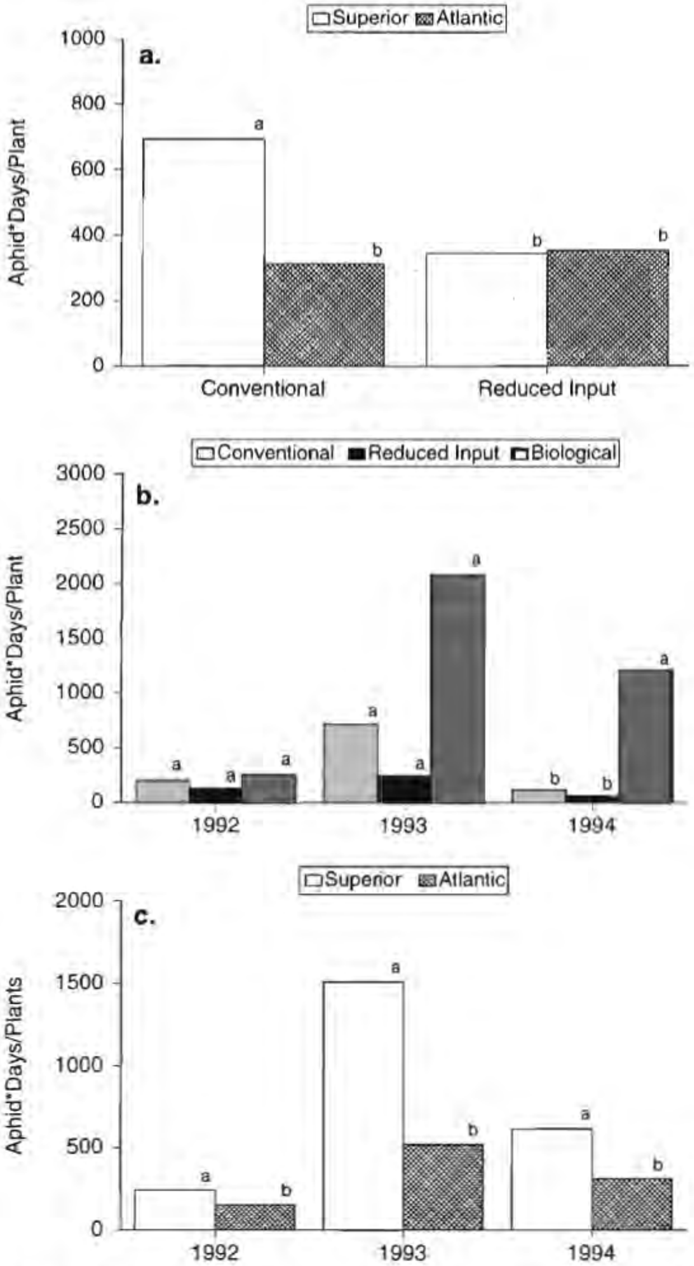


Figure 4.12. Interaction between potato variety and pest management system on total aphid incidence, 1991 (a), effect of pest management system on total aphid incidence, 1992–1994 (b), and effect of potato variety on total aphid incidence, 1992–1994 (c). Bars with the same letter (within a year) are not significantly different (p<0.05).

in 1991. The total aphid population was higher in Superior potatoes that received the CONV treatment compared to Atlantic potatoes that received the CONV treatment and to the BIO control plots regardless of the variety (Figure 4.12a). While significantly higher total aphid densities were observed (Figure 4.12b) in the BIO control plots compared to either the RI or CONV plots ($p \leq 0.05$ in 1994 only), similar trends were observed (Figure 4.12b) for both 1992 ($p=0.10$) and 1993 ($p=0.07$). Between 1992 and 1994, total aphid densities were always higher on Superior than on Atlantic (Figure 4.12c). This finding should be investigated further in more detailed studies.

In 1992, the effect of potato plant nutrition as represented by petiole nitrogen content (%) on total aphid density was assessed. The range per plot of percent nitrogen values was from 0.028% to 1.52%, pooled over all 48 potato plots. A significant linear regression between percent petiole nitrogen and total aphid density was found to exist ($p=0.0001$, Figure 4.13). The relationship has a negative slope, indicating that as nitrogen content of the potato leaf tissue increased, total aphid density decreased. Only 10% of the

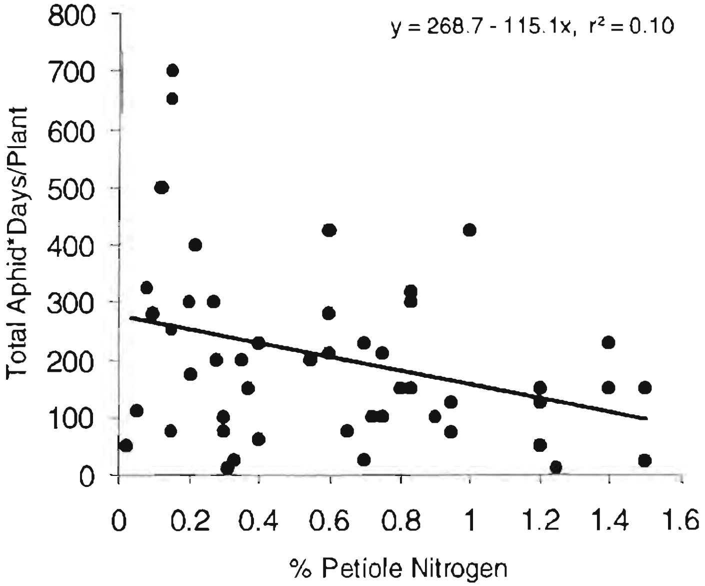


Figure 4.13. Relationship between potato plant nutritional quality as measured by percent petiole nitrogen and total aphid incidence in 1992.

variation in total aphid density, however, was explained by percent nitrogen.

Aphid densities were measured in the barley plots in only one year out of the four-year study, 1992. Insect pest management was not conducted in these plots and only one variety of barley was grown. Therefore, only the soil amendment treatment was examined for its impact on total aphid density. There were significantly ($p=0.01$) more aphids in unamended barley plots (3906.9 ± 237.2 aphid*days/m^2/plot) than in amended barley plots (2855.9 ± 213.9 aphid*days/m^2/plot).

Aphid populations in northern Maine potato-producing areas tend to increase geometrically by the late summer before crashing with the onset of autumn (Shands et al. 1972a). The mean rates of aphid population increase in potatoes over the four years are shown in Figure 4.14. These rates of increase include the effects of insecticides and other factors that might have affected population growth. Despite this, an explosive increase can be seen toward the end of each summer. An exponential model fits the total aphid population data well. The implications of exponential growth (of the form: $N_{(t)} = N_{(0)}*e^{rt}$) are that a combination of reducing the number of colonizing individuals and reducing the per capita birth rate is a more efficacious control strategy than either tactic alone (Table 4.2). Reducing birth rates or intrinsic rates of growth is dependent upon increasing mortality rates with conventional insecticides or through biological control agents such as ladybeetles or insect pathogenic fungi. Reducing the number of colonizing individuals depends upon destruction of proximate overwintering hosts or decreasing the colonization rate via reflective mulches, intercropping, trap cropping, or other interference tactics.

Ladybeetles

The number of species (species richness) of lady bird beetles observed in the study area changed dramatically between 1992 and 1994 (the different species of ladybeetles were not recorded in 1991). In potato, we recorded seven species in 1992, five species in 1993, and seven species in 1994. In barley, we recorded 18 species in 1992 and five species in 1993. Species richness was higher in barley than in potato in 1992, but not in 1993. We compared the ladybeetle abundance of the different species of ladybeetles to determine whether they were similar for the species (a measure of species diversity) between years or between crops within years. Species diversity was significantly different between years in potato (X^2 test, $p<0.0001$) and barley (X^2 test, $p<0.0001$). The species

Table 2. Relative efficiency of two tactics: Reduction of colonization and reduction of net birth rates, for controlling aphids in potato in northern Maine.

% Reduction in Net Birth Rate	Resulting[1] % Reduction in Population
10	15–24
20	30–47
50	58–80
90	80–95
% Reduction in Colonization	**Resulting % Reduction in Population**
10	10
20	20
50	50
90	90
% Reduction in Both Birth Rate and Colonization	**Resulting % Reduction in Population**
10	22–43
50	79–90
75	94–99

[1] Estimates were derived from Parameterized Models (1991–1994) listed in Figure 4.11.

diversity was also different between barley and potato both in 1992 (X^2 test, p<0.0001) and in 1993 (X^2 test, p<0.01). These differences are depicted by the relative abundances of the five most common ladybeetle species in Figure 4.15. In both potato and barley, the seven-spotted ladybeetle (*Coccinella septempunctata* L.) was observed more commonly than the other species of ladybeetles. This species was introduced from Europe into Maine between 1964 and 1969 to supplement native ladybeetles in control of aphids on potato (Shands et al. 1972b). Detailed biological studies on the dynamics of the seven-spotted ladybeetle (C-7) in relation to crop habitat, plant phenology, and aphid prey temporal and spatial distributions have been reported by Ngollo (1994) and will not be discussed here.

Over the three-year period from 1992 to 1994, pest management system effects were observed on C-7 abundance in 1993 (p=0.0008) and 1994 (p=0.001). In 1993 and 1994, the BIO treat-

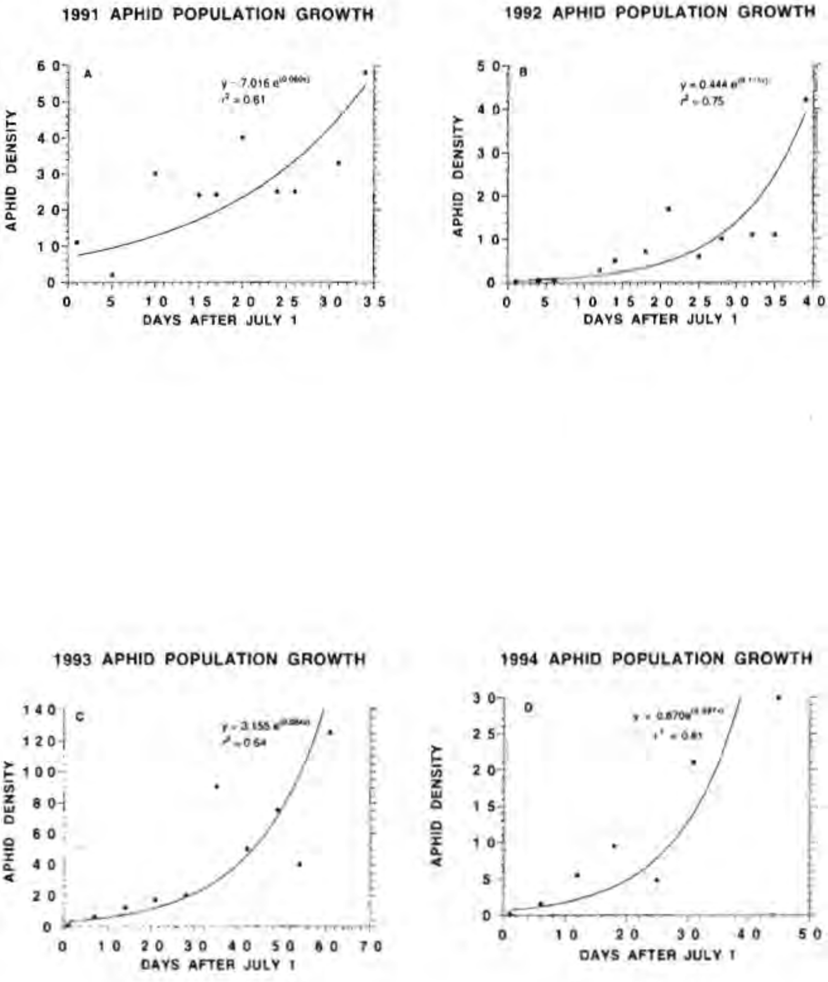


Figure 4.14. Total aphid population growth in potatoes over the growing season after July 1 in 1991 (a), 1992 (b), 1993 (c), and 1994 (d).

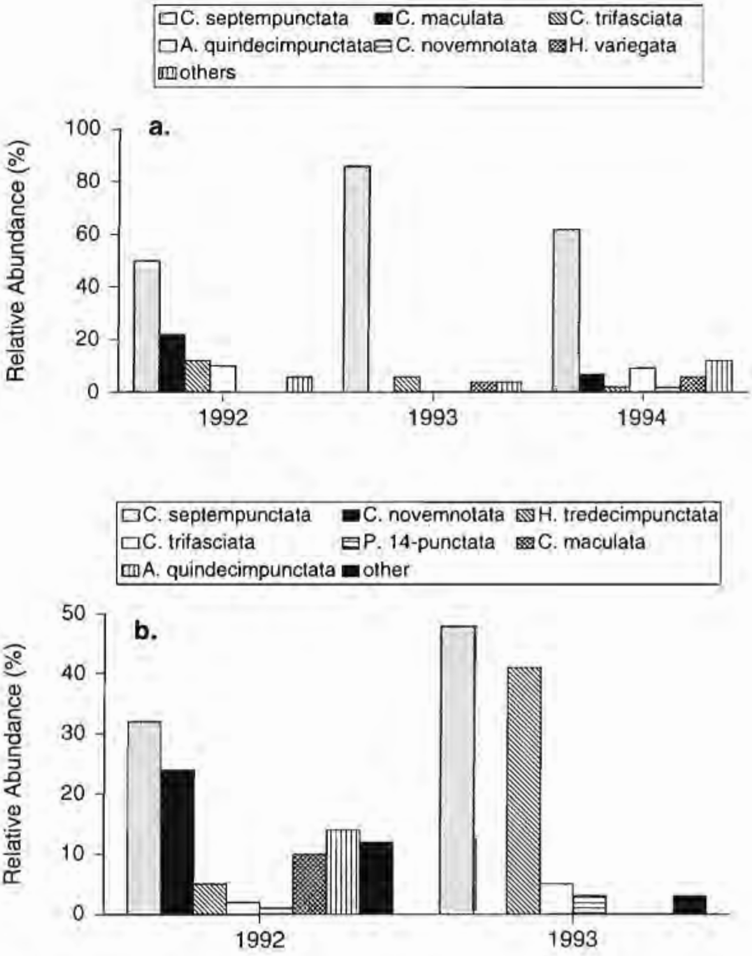


Figure 4.15. Relative abundance of ladybeetle species in potato (a) and barley (b) in 1992, 1993, and 1994.

ment supported higher densities of C-7 than the RI or CONV treatment (Figure 4.16a). This is most likely due to the direct deleterious effects of insecticides on C-7 than it is an aggregation response of C-7 to higher abundance of aphid prey in the BIO plots. Support for this hypothesis comes from results reported by Ngollo (1994), who conducted a series of correlation analyses between C-7 densities and green peach aphid densities, potato aphid densities, buckthorn aphid densities, and total aphid prey densities. He did

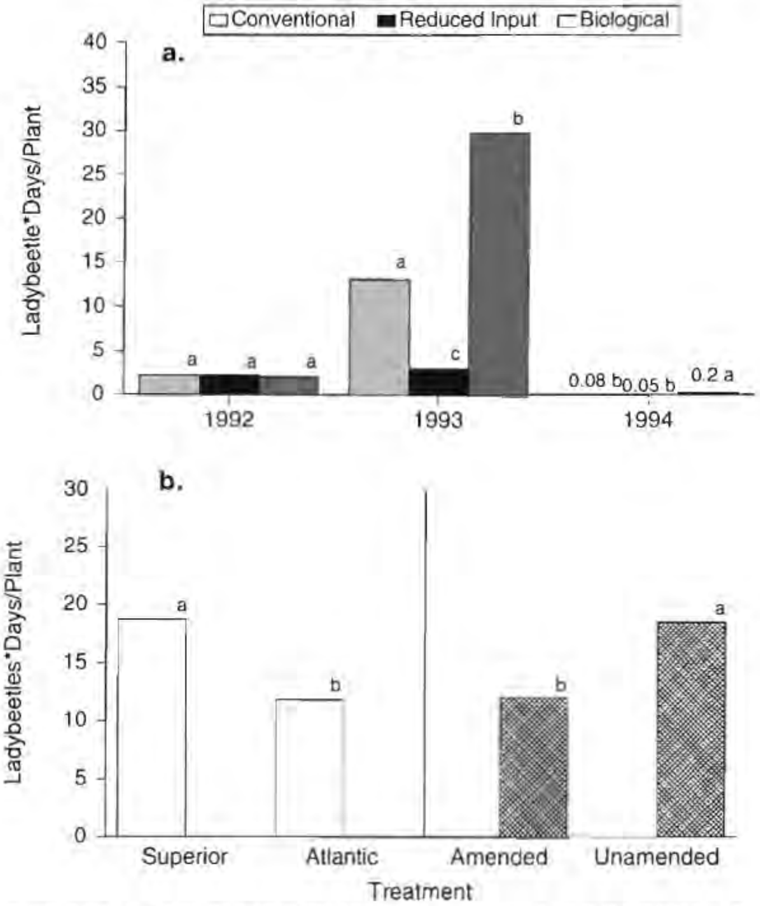


Figure 4.16. Effects of pest management system on C-7 incidence, 1992–1994 (a) and effects of potato variety and soil amendment systems on C-7 incidence, 1993 (b). Bars with the same letter (within a year) are not significantly different (p=0.05).

not find any significant linear relationships between C-7 abundance and aphid prey for the years 1992 and 1993. We found the same to be true for 1994: no significant relationship existed between C-7 abundance and its potential aphid prey in potato.

Potato variety (p=0.03) and soil amendment (p=0.04) treatments affected C-7 abundance in 1993 (Figure 4.16b). We have no hypotheses on why these results occurred. It is possible that a difference in plant architecture could have affected the searching efficiency of adult C-7. It has been found that higher aphid capture rates due to increases in aphid prey density or decreased searching time can increase the amount of time that C-7 adults stay in host plant patches (Karieva 1986).

The pest management systems had strong effects on the total ladybeetle abundance (Figure 4.17a). It is quite clear that the BIO strategy conserved higher numbers of ladybeetles than did the RI or CONV strategy except in 1991. Reducing the number of insecticides may not be the sole answer to conserving ladybeetle populations, since only in 1991 and 1993 did the RI strategy result in higher ladybeetle abundance than the CONV. Figure 4.17a suggests that the type of insecticide may be more important than the number of applications. Figure 4.17b shows that higher numbers of ladybeetles over time were found on Superior than on Atlantic. This is similar to the finding for C-7 discussed previously. Since C-7 constituted more than 80% of the total ladybeetle community in 1993, the results shown in Figure 4.17b probably reflect the dynamics of C-7.

The sampling of the barley habitat for C-7 and total ladybeetle abundance showed that none of the experimental treatments affected the ladybeetle population dynamics. However, Ngollo (1994) did find that in 1992 and 1993, both C-7 and total ladybeetles exhibited a numerical response (changes in aphid prey density resulted in similar changes in ladybeetle density) in barley, but not in potato. This suggests that the dynamics of ladybeetles are different in the two crops.

Generalist Predators

Ground beetles were found in high abundance (1.97 beetles/trap averaged over each growing season) during the two years in which they were sampled (1991 and 1992). Between 49.7% and 78.4% of the total number of ground beetles captured (estimated at 23 species) were *Harpalus rufipes*. *H. rufipes* is unusual in that it is primarily a weed seed predator, although it will feed upon insect prey in the absence of weed seeds (Zhang 1993). The next most abundant species was the generalist predator *Pterostichus melanarius*, which made up 0.3%–25.6% of trap captures, with its highest densities observed in late August. In 1991 and 1992, significantly more ground beetles were found in barley plots than in potato plots ($p<0.001$ and $p=0.003$, for 1991 and 1992, respectively; Figure 4.18). Difference in the frequency of soil disturbance in these two crops may affect beetle densities. Potatoes were cultivated two to four times, whereas barley was not cultivated at all following planting. This phenomenon was also observed in Europe (Scherney 1960). In potato, pest management system did

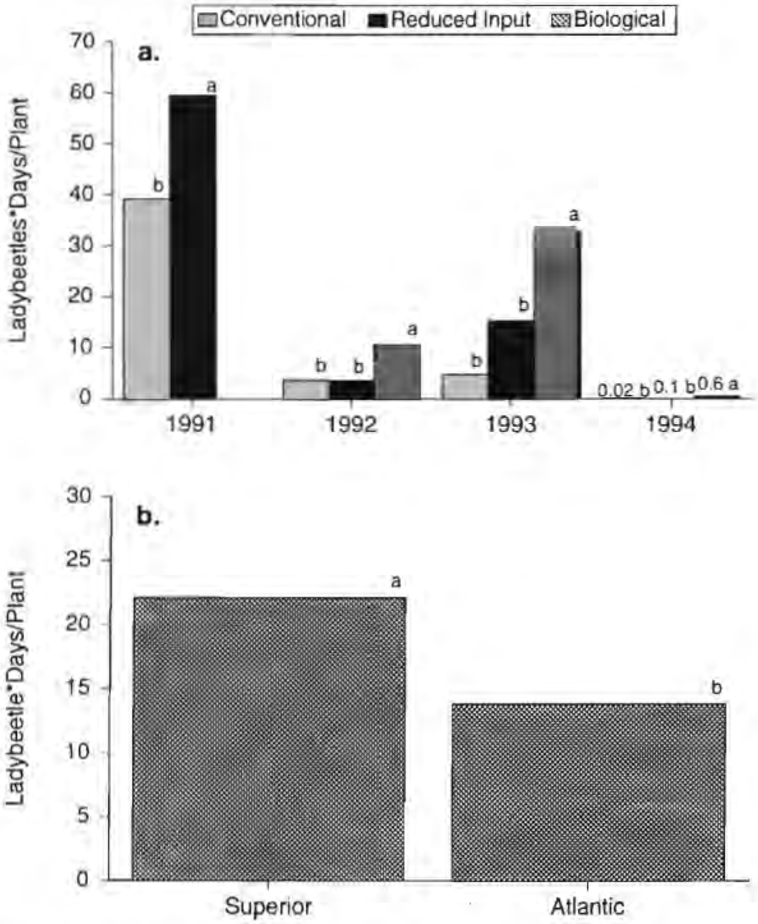


Figure 4.17. Effects of pest management system on total ladybeetle incidence, 1991–1994 (a) and effects of potato variety on total ladybeetle incidence, 1993 (b). Bars with the same letter (within a year) are not significantly different (p=0.05).

not affect the numbers of ground beetles trapped, indicating that the insecticide sprays used to control CPB and aphids do not deleteriously affect these beneficial insects. Ground beetles are almost exclusively nocturnal, seeking shelter under plant debris, rocks, and soil aggregates during the day. This behavior may limit their exposure to lethal concentrations of insecticides. Soil amendments also did not significantly affect the numbers of ground beetles trapped.

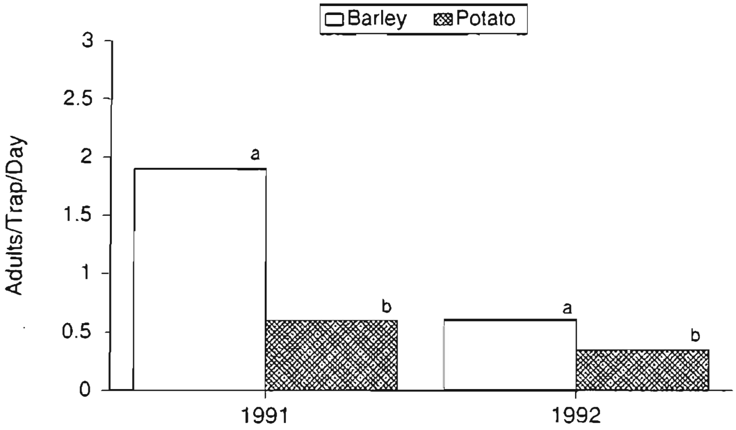


Figure 4.18. Total ground beetle incidence in potato and barley, 1991–1992. Bars with the same letter (within a year) are not significantly different (p=0.05).

Spider densities were extremely low across all treatments during this study, with increased numbers observed toward the end of each growing season. *Tetragnathus* spp. and wolf spiders of the family Locosidae were the dominant spiders found in all four years. In two of the four years (1992 and 1994), densities of spiders were affected by pest management system: the BIO plots had significantly (p=0.04 and p=0.002, 1992 and 1994, respectively) higher densities than the CONV and RI plots (Figure 4.19). This again is probably a result of foliar insecticide sprays in the CONV plots, which kill a larger percentage of the spiders than the more selective materials used in the BIO plots. Similar trends were not observed in the years 1991 and 1993 when densities were low in all plots. The relationship between spider densities and CPB small and large larval densities was examined with regression analysis. No significant relationship was found. Some variety effects on spider densities were observed; however, they were not consistent between years. In 1992, spiders were significantly more abundant in the Atlantic plots compared to the Superior plots (p=0.072, Atlantic = 4.32 spider*days/plant and Superior = 2.96 spider*days/plant). In 1993, however, spiders were more abundant in Superior compared to Atlantic (p=0.074, Atlantic = 1.46 spider*days/plant and Superior = 2.46 spider*days/plant). In 1992 and 1993, the total aphid density was also affected by potato variety. However, in both years greater densities of aphids were found on Superior than on Atlantic

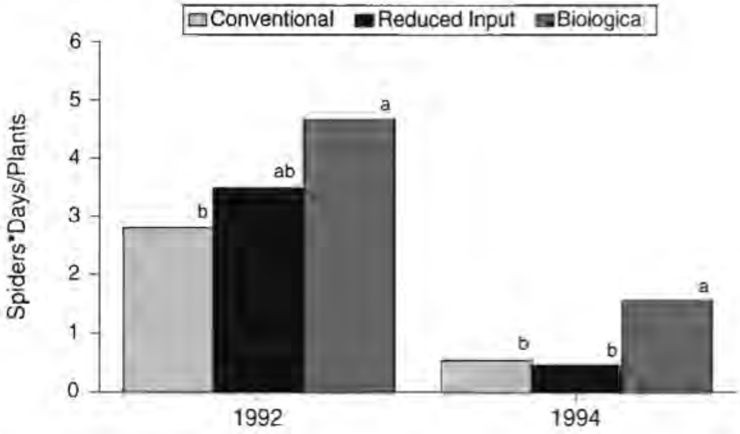


Figure 4.19. Effect of pest management systems on total spider incidence in 1992 and 1994. Bars with the same letter (within a year) are not significantly different (p=0.05).

(p=0.006 and p=0.003), thus spider abundance as affected by variety does not appear to be related to aphid prey abundance. Spiders are very susceptible to desiccation, and they tend to inhabit moist microclimates (Borror and Delong 1964; Foelix 1982). This association with a moist habitat might have resulted in the variety effect on spider density if the relative difference in size and LAI of the two varieties in these years resulted in a difference in moisture stress to the spider community.

The spined soldier bug (*Podisus maculiventris*) was not abundant in any of the plots during the four years of the study (estimated seasonal densities ranged from a low of 0.008/plant in 1994 to a high of 0.04/plant in 1992). This predator is considered the major arthropod natural enemy of CPB in northern New England. Thus, we have to conclude that in northern Maine there is little potential for designing sustainable agricultural cropping systems that rely upon native insect predators to regulate densities of CPB. None of the experimental treatments applied to the plots had any significant effect on *P. maculiventris* abundance. This is not surprising considering the difficulty in detecting such effects given the low densities. Regression analysis was performed to detect the level of variation in CPB egg and small and large larval densities and the densities of *P. maculiventris* (1991–1993 data only). No relationships were found to exist, suggesting that *P. maculiventris* was not exerting a significant level of predation pressure on potato beetle populations from 1991 to 1994.

FUTURE

One goal of the Potato Ecosystem Project is to elucidate and describe the effects of present and alternative soil and pest management practices on the ecological interactions that affect potato production. We have pursued one approach, a large-scale field study, over the past four years to gain an understanding of the ecological and economic dynamics in the northern Maine potato ecosystem. We plan to continue this approach to learn more about the pattern of changes that occur over time with regards to particular management tactics and strategies.

We have also begun to use a second approach to further our understanding of this ecosystem, computer simulation modeling. This approach involves first identifying the significant relationships and/or interactions that capture the main dynamics of the northern Maine potato ecosystem. This is generally called the conceptual modeling phase. Much of the insight for this stage comes from ecological theory, researcher experience, and the relationships that we have defined from our large-scale and component field studies. Figure 4.20 is an example of a conceptual model for weed dynamics as affected by tillage, cultivation, and rotation crops. A subset of many possible factors that influence weed seed dynamics is shown. This subset comprises the factors that we initially believe to be important to include in a computer simulation model. The modeling process is an iterative process, and as we use the model, some factors we initially chose may be found unimportant while others that we have not considered may be necessary to include.

The next phase is to construct the mathematical relationships that will simulate or "mimic" the real world dynamics. Figure 4.21 is a pictorial representation of a series of differential equations (Fan et al. 1991), which are used to simulate the temperature-dependent, time-varying distributed development of an insect population "moving through" one life stage to another. The type of data needed for quantifying the relationship of temperature with insect development is also depicted in Figure 4.21: daily average temperature from the field, the average rate of development (in days) of an insect population for a specific stage (such as first instar CPB), and an estimate of the variation of development times for the insect population at different temperature regimes.

The third general phase of simulation modeling is the validation phase. The objective in this phase is to compare the performance of model output runs with an independent set of field observations. Figures 4.22 and 4.25 depict model runs of our CPB

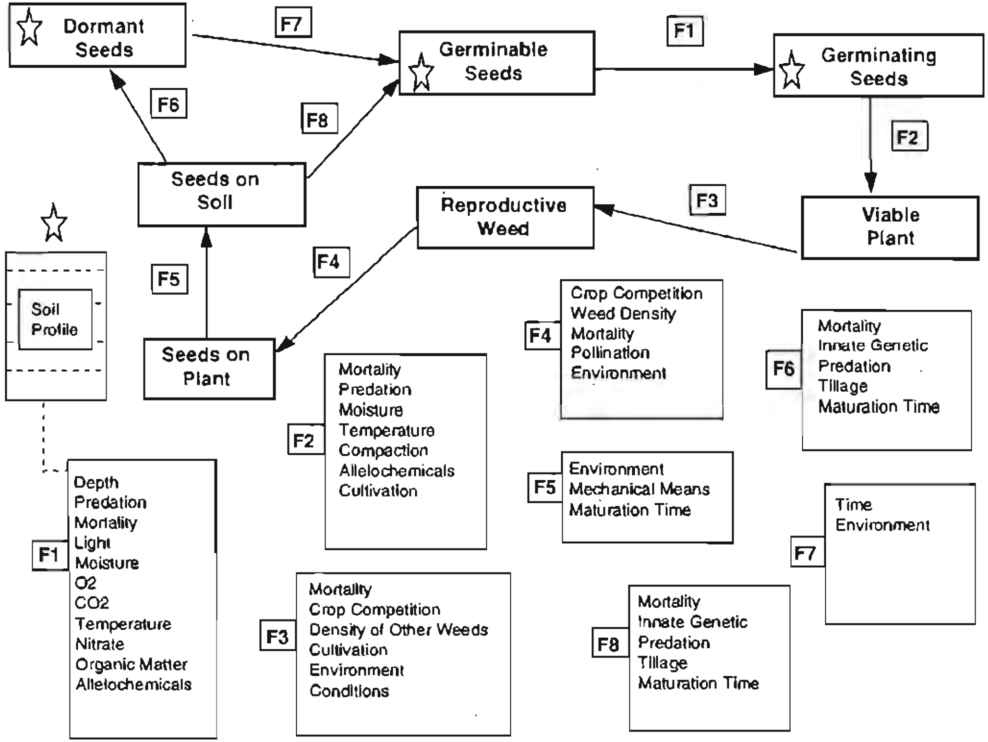
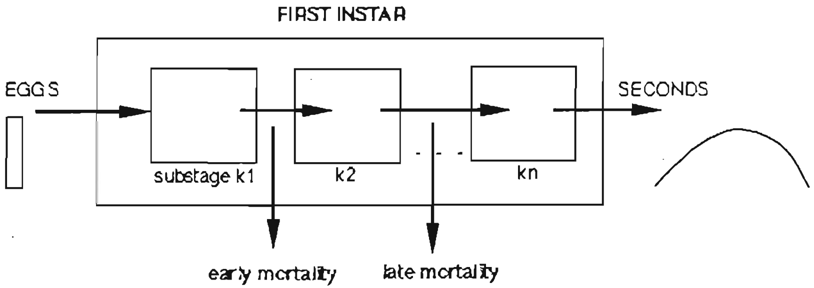


Figure 4.20. Conceptual model of weed seed dynamics, the components, and factors that affect densities of seeds in the potato-weed seed bank.

TIME-VARYING DISTRIBUTED DELAY WITH ATTRITION



SIMULATED WITH "K" DIFFERENTIAL EQUATIONS

THE ERLANG DISTRIBUTION IS EQUIVALENT TO A SET OF K ORDER LINEAR DIFFERENTIAL EQUATIONS.

THEREFORE, THE CHOICE OF "K" DETERMINES THE SHAPE AND VARIANCE OF THE FLOW RATE OF INDIVIDUALS IN THE POPULATION.

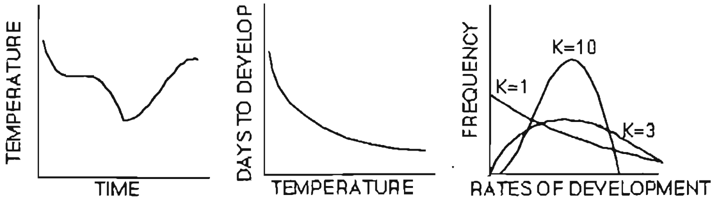


Figure 4.21. Illustration of a k-cascaded set of differential equations that can be used to simulate (via computer) the individual progression of insects in a population through their life stages.

simulation model using weather data collected in the Potato Ecosystem large-scale plots during 1992 and 1993. Data from the BIO plots were used to evaluate the model. Cumulative percent occurrence of each stage was used to compare the model predictions with the observed field data to eliminate confounding due to absolute density changes, which resulted from the application of control tactics. In 1992, observed cumulative spring adult emergence was well predicted from 10% to 60% emergence. However, model predictions lagged behind observed emergence a few days between 60% and 98% emergence (Figure 4.22a). The cumulative egg-laying predictions in 1992 lagged behind observed egg laying a few days for most of the early summer, although at the end of the oviposition period the model predictions lagged behind the observed by ca. 5 days (Figure 4.22b). In 1993, model predictions for CPB phenology in the BIO plots was very close to that observed except for the summer adults (Figure 4.23). The predictions for summer adults were much earlier than observed. This might be explained by *B. bassiana* infection, which slows CPB development. In general, the CPB population model appears to simulate the phenology in the northern Maine potato ecosystem.

The fourth phase of a modeling approach is to use the model experimentally to learn more about the dynamics of the system. Linking the CPB model with a *Beauveria bassiana* infection model, we are beginning to explore timing of foliar applications of *B. bassiana* for CPB control. Figure 4.24 shows the results of CPB population densities of both noninfected (spring adults, eggs, first instar, and second instar CPBs) and *B. bassiana*-infected CPB life stages (first, second, third, and fourth instar CPBs) from a single high dose application (1×10^{14} conidia/ha) applied at peak fourth instar larval density. Figure 4.24a shows that although the application was timed for peak fourth instar density, some first and second instars are affected by the application, and as a result, a dip in the first and second instar healthy population occurs. Figure 4.24b shows that because of the timing the infected population of fourth instar CPB is larger than the other infected populations even though the fourth instars are less susceptible to the *B. bassiana* applications. The effect of the spray on the late instars, pupal densities and summer adults is shown in Figure 4.24c. Figure F6 shows how with a single spray of *B. bassiana* at 1×10^{-13} conidia/ha (applied at 7 a.m. in the morning during 1993), the time that resulted in the highest reduction in potential defoliation and summer adult densities was during the peak occurrence of CPB second instars. Table 4.3 lists the results of a series of simulations

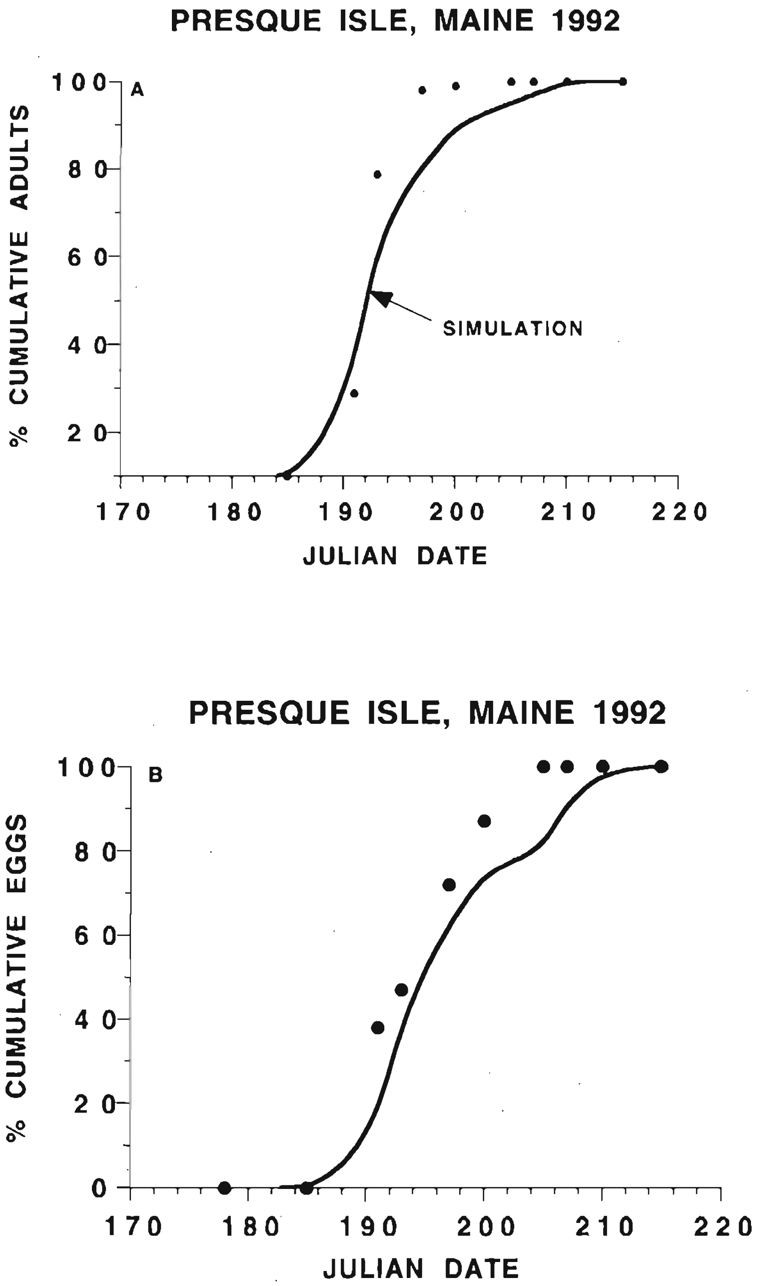


Figure 4.22. Comparison of field observations and computer simulation results of cumulative Colorado potato beetle spring adult (a) and egg (b) incidence in the biological pest management system during 1992.

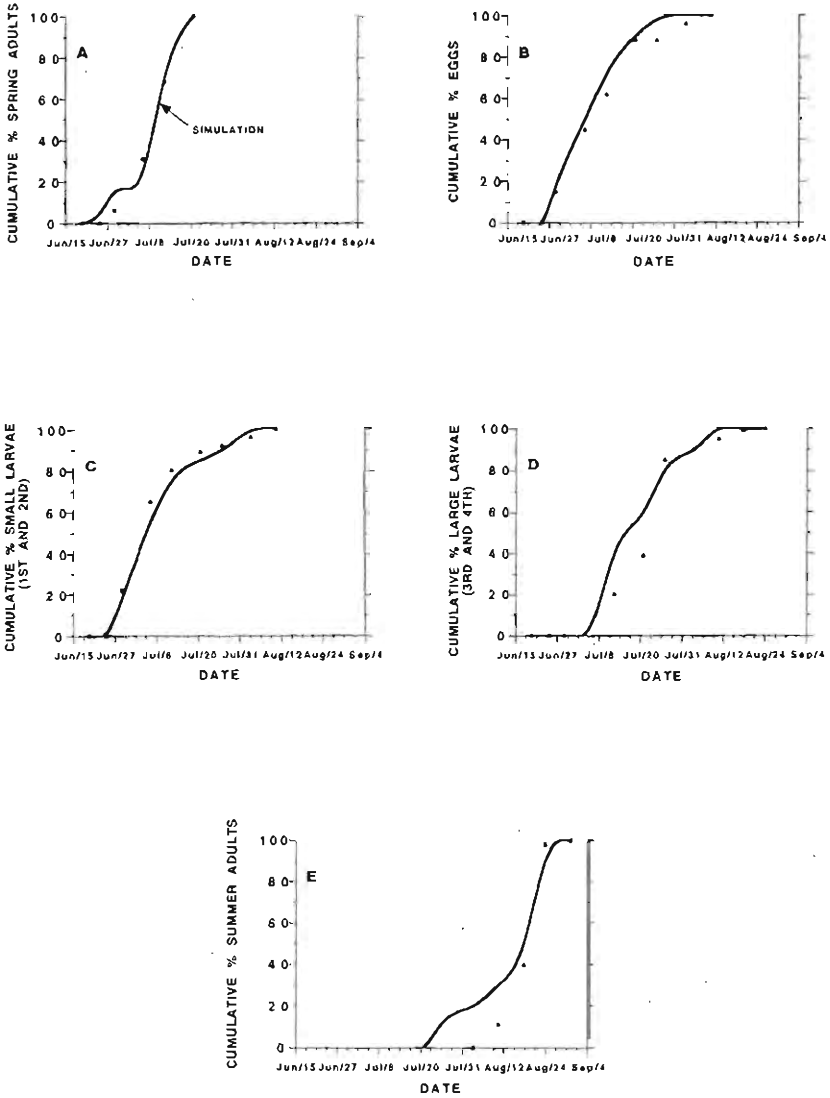
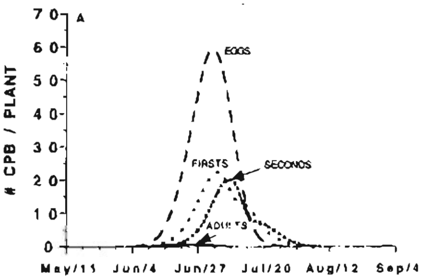
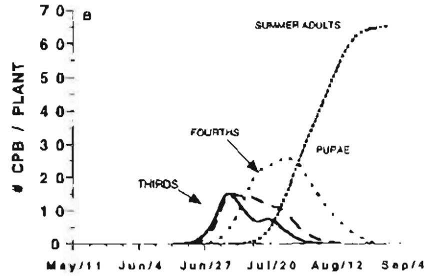


Figure 4.23. Comparison of field observations and computer simulation results of cumulative Colorado potato beetle spring adult (a) and egg (b), small larvae (c), large larvae (d), and summer adult (e) incidence in the biological pest management system during 1993.

HEALTHY SPRING ADULTS, EGGS, FIRSTS, AND SECONDS



HEALTHY THIRDS, FOURTHS, PUPAE, AND SUMMER ADULTS



INFECTED LARVAE

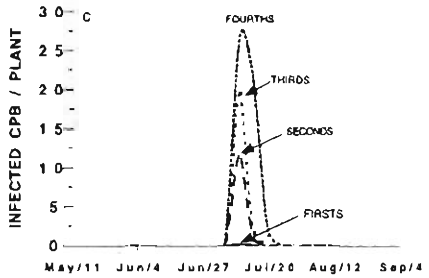


Figure 4.24. Computer simulation results of Colorado potato beetle incidence using daily weather data (air temperature, soil temperature, soil moisture) from Stillwater, ME, a single foliar application of Beauveria bassiana applied at peak fourth instar density and an initial spring colonization density of 2.0 adults per plant. Life stages shown are healthy spring adults, eggs, 1sts, 2nds (a); healthy 3rds, 4ths, pupae, summer adults (b); and infected 1sts, 2nds, 3rds, 4ths (c).

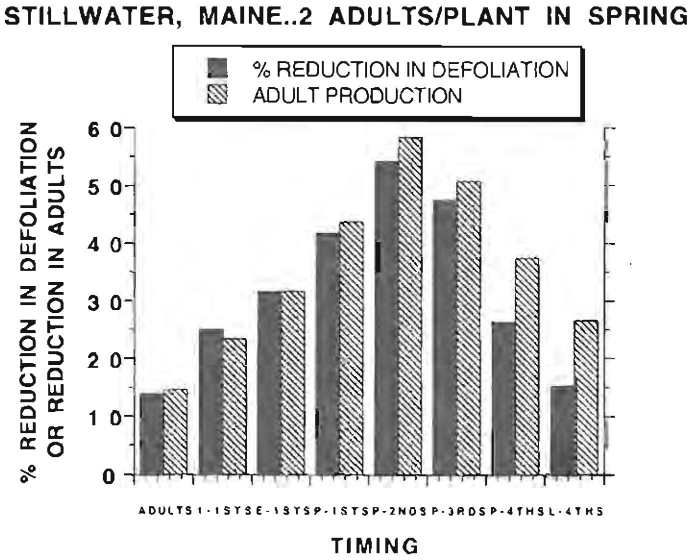


Figure 4.25. Computer simulation results of single foliar application using daily weather data (air temperature, soil temperature, soil moisture) from Stillwater, ME, and an initial spring colonization density of 2.0 adults per plant. The disease was applied at either peak spring adults, initial appearance of 1sts, early (20%) 1sts, peak 1sts, peak 2nds, peak 3rds, peak 4ths, or late (last 20%) 4ths.

designed to assess the relative efficacy of multiple applications of *B. bassiana* aimed at different points in the CPB population age structure. This is not an exhaustive set of simulation runs for all possible CPB life stage combinations and weather conditions. It does, however, point out a few relationships that could be tested in a field experiment. First, Table 4.3 suggests that more sprays do not necessarily result in more CPB control. Also, if the grower waits until the peak third or fourth instars are present in the field, control will be inadequate. The best stages to target are the first and second instars. However, a cluster of sprays aimed at the peak first instars is not as effective as a strategy that spaces out the sprays over the early first to peak second instar occurrence.

The last phase of the modeling approach is to reassess the initial model structure and to determine where changes should be made or where experiments should be performed that will aid in developing better parameter estimates for specific relationships that significantly affect the dynamics of the modeled system (sensitivity analysis). The modeling approach is an iterative pro-

Table 4.3. Simulation results of different application strategies of *B. bassiana*.

Number of Sprays	Target Life Stage[1,2]	% Defoliation Reduction	%Adult Density Reduction
2	E-1,P-2	65	75
	P-1,P-2	71	77
	P-2,P-3	67	75
	P-2,P-4	64	79
3	P-3,P-4,L-4	50	74
	E-1,P-1,P-2	83	90
	P-E,P-1,P-4	75	82
	P-1,P-1,P-1	78	85
	E-1,E-1,E-1	55	57
	P-4,P-4,P-4	38	60
4	P-E,E-1,P-3,L-4	78	86
	E-E,E-1,P-1,P-4	78	85
	E-1,P-1,P-1,P-2	86	90
	E-1,P-1,P-2,P-3	90	94
	E-1,P-4,L-4,L-4	40	65

[1] The first letter of the target life stage represents the time in the stage of application: E=early, at first 20% occurrence of stage; P=peak of life stage; L=late, at last 20% occurrence of stage.

[2] The second letter or number refers to the CPB life stage targeted: E=egg stage, 1=first instar, 2=second instar, 3=third instar, 4=fourth instar.

cess, and at this point our research scientists are at different phases of the process for the northern Maine potato ecosystem.

So far we have begun to construct and modify existing models of

1. CPB population dynamics;
2. Dynamics of the insect disease fungus *Beauveria* bassiana;
3. Potato plant growth (modifying an existing model developed in the northcentral U.S., SPUDGRO (Johnson et al. 1988); and
4. Weed dynamics as affected by tillage, cultivation, and rotation crops.

The goal is to use these models individually and to link them together to explore alternative management options and resulting dynamics within the northern Maine potato ecosystem. Results from these simulation studies can then be used to help formulate hypotheses for detailed field studies to verify the findings.

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V. Plant Diseases

David H. Lambert and Bacilio Salas

INTRODUCTION

Potatoes in the Northeast are subject to a number of diseases. With some of these, year-to-year losses vary within a limited range. With others, losses in a given year may be negligible or severe, often in response to the season's weather or inoculum conditions. The severity of most diseases is affected by variety, rotation, fertility, pesticides, harvest, and other management decisions. Shifts in management practices may therefore produce either unexpected disease consequences or predictable changes of unknown magnitude. For these reasons, the severities of common diseases have been quantified in the Potato Ecosystem plots, subject to their presence.

Late blight (*Phytophthora infestans*) and early blight (*Alternaria solani)* are the two most common foliar diseases of potato. Severe epidemics of late blight are sporadic, but present the greatest potential threat to potato production. Late blight was severe in 1993. *P. infestans* is an obligate parasite, and it survives the winter only as mycelium in infected tubers, whether these are for seed, in cull piles, or volunteers left in the ground.

Early blight occurs in every growing season and wherever potato is grown. The name "early blight" is misleading, because susceptibility to the disease increases as the foliage matures. *Alternaria solani* survives the winter in infected plant debris or in the soil surface.

Rhizoctonia disease (black scurf), caused by *Rhizoctonia solani*, is present in most potato fields, and populations have increased with shortened crop rotations. Losses to *Rhizoctonia* include decreased tuber yields resulting from infection of stems and stolons and decreased marketability of sclerotia-bearing, small or deformed tubers. Both soil and tuber-borne inocula are important in disease development, making it difficult to control this disease. The species *Rhizoctonia solani* is composed of several subspecies designated as "anastomosis groups." Three of these, AG-3, AG-4, and AG-5, infect potato.

In 1994, patterns of early senescence developed that were thought to be disease-related. Vine death occurred sooner in the biological (BIO) than in the conventional (CONV) or reduced input (RI) plots, and this was more evident with the early variety Superior than with Atlantic. Vigor appeared better in the nutrient management plots rotating from pea/vetch/oat than in plots following clover/barley. The fungus *Colletotrichum* (cause of "black dot") was evident in many stems, and some stems were pinkish, suggesting that *Verticillium* early dying was involved. Superior is more susceptible to *Verticillium* than Atlantic, Colletotrichum often follows *Verticillium*, and early dying and pink stems are symptoms of *Verticillium* infection in potatoes. However, the relationships to pesticide and fertility treatments were not clear.

METHODS

Early and Late Blight

Three foliar disease management strategies were studied for control of early and late blight in 1993 (Table 5.1). In this year, environmental conditions highly favorable for late blight occurred from 25 July on, and the strain(s) of *Phytophthora* that developed in the plots were resistant to Ridomil. Severity of early and late blight, i.e., the percentage of diseased leaf area, was assessed visually using standard scales. Late blight was assessed on ten plants per plot on 18–19 August, and on 550–650 plants per plot (four rows) on 26–28 August. Early blight was evaluated on ten plants per plot on each date. To determine the incidence of late blight on tubers, all tubers with symptoms of rot in five samples of 50 tubers each per plot were collected during harvest. Formation of sporangia on tuber pieces placed on water agar culture plates was required for a tuber to be counted. In 1994, lesions were detected in a single plot before the onset, in early August, of environmental conditions unfavorable for disease. On 8 September, surveys of single rows in each plot did not reveal any active lesions or other evidence of significant late blight infection. Because senescence and mortality were advanced in specific treatments (BIO, unamended), early blight readings were not made.

Rhizoctonia

Disease evaluations

In 1993, eight plants were removed at random from each plot on 6–8 July, ten plants were sampled on 26–30 July (full flowering), and 15 tubers were sampled during harvest (21–24 September). The root system of each plant was washed and examined for disease symptoms on stems and stolons. The extent of lesion development (% area) was rated visually, and disease severity was expressed as the *Rhizoctonia* stem lesion index (Weinhold). Incidence of *Rhizoc-*

Table 5.1. Fungicide treatments applied in 1993.

Treatment	Material	Rate (lb/A)	Application #	Application Interval	Application Dates
Conventional	Dithane DF	1.5	7	7	14/7–23/8
	Ridomil MZ 58		2	14	28/7,11/8
Reduced Input	Dithane DF	2.0	7	7	24/7–23/8
	Ridomil MZ58		1		11/8
Biological	Kocide	2.0	5	10	14/7–23/8
	Ridomil 2E		1		23/8

tonia on stolons was calculated based on all stolons examined on each plant (26–30 July). Tubers were washed and rated visually for the percentage of surface covered by sclerotia (black scurf). Disease severity was expressed as the average of infection for all tubers assessed. In 1994, ten plants per plot were sampled from 1–9 August.

Isolations

Isolations of *R. solani* from stems were made from samples collected on 6–8 July. Samples collected on 26–30 July were used for isolations from stolons. On each date, one heavily infected plant per plot was used for isolations. Five 0.5-cm segments from the interface between healthy and diseased tissue were cultured. These were blotted with paper towels and placed on water agar (WA) amended with 100 ppm streptomycin sulfate. Sclerotia on tubers were also excised and placed on WA plates. Culture plates were incubated under darkness at room temperature (20–25 °C) for 36–48 hr. Cultured fungi resembling *Rhizoctonia* were hyphal tipped and transferred to half-strength potato-dextrose-agar slants. A total of 232 *Rhizoctonia*-like isolates were recovered and stored at room temperature.

Anastomosis group typing

Two sets of AG-3, AG-4, and AG-5 test strains were used to determine anastomosis group identities. All field isolates were first classified on their morphological appearances. Isolates appearing to be AG-3 were tested first with that group, and negatives were then paired with AG-4 and AG-5 test strains. Anastomosis groups were determined by placing one three-day-old mycelial disk of a tester isolate at the center of a 9-cm plastic petri plate on a thin film of WA, with three unknowns placed around the tester at a distance of 2 cm. These plates were incubated under darkness at room temperature (20–25 °C) for 30–48 hr. The overlapping area of advancing hyphae between the tester and each unknown was removed, stained, and observed for the presence of at least five anastomosis points. Isolates were stained with Safranin O to determine their nuclear condition.

Early Senescence

To demonstrate that *Verticillium* was infecting the plots and that its severity was related to the appearance of the field, sap squeezed from stems was plated into two types of selective media. Then fungal colonies developing in the plates were identified and counted. Three lower stem pieces from each plot were surface-sterilized and pressed to produce 0.1 ml liquid for each plating. Colony counts were related to July and August field cover, vigor, Vmax, and the variety, rotation, and pest management treatments.

RESULTS AND DISCUSSION

Early Blight

Foliar symptoms of early blight were not affected by fungicide treatment or amendment, but were more severe in Superior, the earlier of the two potato varieties (Table 5.2). The implications of these results are that fungicide applications to control early blight on Atlantic may be initiated later than on Superior and the frequency of fungicide sprays for these two varieties may be different.

Late Blight

Nutrient management systems did not affect late blight. Severity of late blight in the three disease management strategies was not significantly different on 18–19 August (not shown), but was higher in BIO plots rather than the RI or the CONV plots on 28 August (Table 5.2). At harvest (21 September), 93% of tubers with symptoms of rot were infected by *Phytophthora infestans*. Overall incidence of late blight was 7.4%, but infection ranged from 1% to 28%. Although differences were not significant, RI and CONV plots had more infected tubers than the BIO plots. Under severe disease pressure, Dithane DF was significantly more effective than Kocide in controlling late blight on foliage, but tuber blight incidence was about 50% lower (nonsignificant) in Kocide-treated plots. This was presumably due to more effective inhibition of sporangia and zoospore germination of *P. infestans* by this compound. Copper

Table 5.2. Effects of fungicide treatments on severity of early and late blight symptoms[1] in 1993.

Treatment	Early Blight	Late Blight	
	Foliage	Foliage	Tuber
Pest Management System			
Conventional	4.8 a[2]	0.6 a	8.4 a
Reduced Input	6.4 a	0.4 a	9.5 a
Biological	6.1 a	3.2 b	4.2 a
Variety			
Superior	9.2 b	1.1 a	5.6 a
Atlantic	2.2 a	1.7 b	9.2 b
Amendment			
None	6.3 a	1.4 a	--
Compost/manure[3]	5.3 a	1.4 a	--

[1] Percentage of leaf surface area or percentage of tubers diseased.
[2] Means followed by the same letter do not differ significantly at (p = .05).
[3] 10 tons/A cull potato compost + 20 tons/A beef manure.

(Kocide) is highly toxic, and reduces germination of *P. infestans* sporangia in soil. Both standard protectants and copper fungicides may be necessary to adequately control late blight. Metalaxyl did not control the epidemic of late blight in this experiment or in the fungicide trials elsewhere on Aroostook Farm, as metalaxyl-resistant strains became widespread during the 1993 season.

The greater severity and incidence of late blight on Atlantic compared with Superior contrasts with results of other studies. Vigor ratings of plots on 25 August indicated that Superior was beginning to senesce whereas plots with Atlantic were still vigorous.

Rhizoctonia

Anastomosis group typing

All 134 isolates of *R. solani* obtained from tuber-borne sclerotia were identified as members of the AG-3 anastomosis group (Table 5.3). Of the 66 *R. solani* isolates examined from stems, 37 were AG-3, 13 were AG-5, and six were AG-4. Eight multinucleate isolates from stems failed to anastomose with these three groups and remain to be identified. Two binucleate isolates were also recovered from stems (Table 5.3). Of the 32 isolates obtained from stolons, 30 were AG-3, and two were AG-5.

Table 5.3. Anastomosis groupings of *Rhizoctonia solani* obtained from stems, stolons, and tubers in 1993.

Anastomosis Group	Number of Isolates Stem Lesions	 Stolon Lesions	 Sclerotia (tuber)	 Total
AG-3	37	30	134	201
AG-4	6	0	0	6
AG-5	13	2	0	15
AG-NO[1]	8	0	0	8
Binucleate	2	0	0	2
Total	66	32	134	232

[1] Multinucleate isolates that failed to anastomose with AG-3, AG-4, or AG-5.

The effects of potato varieties, nutrient management, and crop rotation on *R. solani* AG-types are summarized in Table 5.4. As expected, AG-3 was the predominant type recovered (86.7%), with AG-4 and AG-5 at 6.5% and 2.6%, respectively (Table 1). Isolates of AG-3 from stolons were recovered in comparatively greater frequency from Atlantic, in unamended plots, and when potato was rotated with barley plus red clover. All sclerotia were type AG-3. Recovery of AG-4 was limited to stems in barley/red clover plots. AG-4 has previously been reported as infecting feeder roots under greenhouse conditions or causing superficial lesions, but its biology is otherwise not well understood.

Table 5.4. Numbers of isolates of *Rhizoctonia solani* in relation to variety, nutrition and rotation treatments.

	AG-3		AG-4		AG-5	
Treatment	Stem	Stolon	Stem	Stolon	Stem	Stolon
Variety						
Atlantic	16	17	3	0	5	2
Superior	18	13	3	0	8	0
Nutrition						
Fertilizer	17	17	4	0	9	1
Fertilizer/Compost[1]	20	13	2	0	4	1
Rotation Crop						
Pea/vetch/oat	22	80	0	2	0	
Clover/barley	15	22	6	0	11	2

[1] 10 tons/A cull potato compost + 20 tons/A beef manure.

Rhizoctonia disease severity

In 1993, incidence and severity of *Rhizoctonia* on stems, stolons and tubers were higher on Atlantic than on Superior (Table 5.5). This was consistent at all dates and plant parts examined. The incorporation of potato cull compost and cow manure increased incidence and severity of *Rhizoctonia* in 1993. This treatment was not applied to the 1994 crop. In 1993, the previous pea/vetch/oat rotation reduced *Rhizoctonia* disease more effectively than the barley/red clover rotation. In 1994 no differences were found. (Table 5.5). No interactions were significant. *Rhizoctonia* severity was affected by variety and pest treatment in 1994, but these effects depended on the plant part (stem or stolon) evaluated (Table 5.6).

Anastomosis group typing—*Rhizoctonia* disease

In 1993, incidence and severity was higher on stems, stolons, and tubers of Atlantic than on those of Superior. In 1994, stolon severity was again higher on Atlantic, but stem severity was higher on Superior. This suggests that the disease pressure on Superior was particularly high early in the growing season. The degree of seed piece contamination by *Rhizoctonia* was not assessed in either

Table 5.5. *Rhizoctonia* incidence and severity on potato stems and stolons averaged over variety, rotation, and fertility treatments in 1993.

	Incidence (%)				Severity	
Treatment	Stem 7/7	Stem 26/7	Stolon 26/7	Tuber 21/9	Stem[1] 26/7	Tuber 21/9
Variety						
Superior	46.7 a[2]	86.3 a	39.1 a	46.7 a	17.4 a	1.1 a
Atlantic	33.2 b	79.1 b	29.8 b	32.2 b	10.7 b	0.7 b
Rotation Crop						
Pea/vetch/oat	29.5	81.4 b	NA	38.3	12.2 b	0.8
Barley/clover	45.2	83.3 a	NA	40.0	15.0 a	0.9
Nutrition						
Fertilizer	36.9 b	79.5 b	33.5	33.9	13.7	0.9
Fertilizer/ Compost[3]	42.9 a	85.9 a	35.5	45.0	14.4	0.9

[1] Rhizoctonia stem lesion index.

[2] Treatment means followed by the same letter do not differ significantly (p = .05).

[3] 10 t/A cull potato compost + 20 t/A beef manure.

Table 5.6. *Rhizoctonia* severity on potato stems and stolons averaged over variety, rotation, and pest control treatments in 1994.

Treatment	Percentage Surface Area Affected Stem	 Stolon
Variety		
Superior	19.6 b[1]	3.3 a
Atlantic	13.3 a	5.9 b
Rotation Crop		
Pea/vetch/oat	16.3 a	4.8 a
Barley/clover	16.5 a	4.4 a
Pest Management Treatment		
CONV	15.5 ab	4.3 a
RI	20.3 b	4.2 a
BIO	13.6 a	5.4 b

[1] Means followed by the same letter do not differ significantly ($p = 0.05$).
CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

year. The poor emergence of Superior in 1994 is consistent with the possibility that seed of this variety was either heavily infested with *Rhizoctonia* or that poorly developing Superior plants were more susceptible to early stem infection by *Rhizoctonia*.

Early Dying

Verticillium albo-atrum and/or *V. dahliae* were found in most of the samples, and *Colletotrichum* was recovered from some (Table 5.6). Other fungi occurred infrequently in low numbers. Average colony counts per 0.1 ml sap are given in the following table in comparisons of variety, pest management, and rotation treatment means.

July vine coverage was sparser in Superior than in Atlantic, but not otherwise related to disease or treatment. In August, heavier coverage was most associated with previous rotation to pea/vetch/oat. To a lesser extent, lower vine coverage was associated with higher *Colletotrichum* counts in the BIO system.

Higher stem vigor was associated with pea/vetch/oat, *Colletotrichum*, and the BIO pest management system. Higher VMAX was associated with pea/vetch/oat, low *Colletotrichum* and *Verticillium* counts, and with their covariates—the Superior and biological treatments.

Although fungal counts were nearly twice as high after the clover/barley rotation, differences were not statistically signifi-

Table 5.6. Colony counts of *Verticillium* or *Colletotrichum* per 0.1 ml in two agar media averaged over variety, pest management, and rotation treatment means.

Treatment	*Verticillium* (medium 1)	*Verticillium* (medium 2)	*Colletotrichum* (medium 1) number	*Colletotrichum* (medium 1) incidence
Variety				
Atlantic	63	72	18	38
Superior	572 **+	785 **	116 **	75
Pest Management Treatment				
CONV	127	63	5	63
RI	125	62	4	31
BIO	1005 **	714 **	187 **	75
Rotation				
Pea/Vetch/Oats	281	209	48	42
Clover/Barley	557 NS	350 NS	83 NS	71 NS

+ ** indicates statistical significance (p = 0.01) NS indicates lack of significance. CONV = conventional, RI = reduced input, and BIO = biological pest management systems.

cant. Elevated counts are reasonable in treatments with less vigor and earlier senescence.

It appears that *Verticillium* and *Colletotrichum* are involved in the premature senescence particularly apparent in the Superior and the BIO plots. The reasons why the BIO plots have higher fungal counts have not been determined. Differences in fungicides (Kocide vs the more effective Maneb) might affect foliar infection by *Colletotrichum*, but do not explain the differences in colonization by *Verticillium*, for which foliar infection is of minor importance. Higher weed populations in the BIO system might contribute to increased *Verticillium* inoculum levels, but are unlikely to provide substantially more inoculum than potatoes themselves. The two major weeds in these plots, lambsquarters (*Chenopodium album*) and hempnettle (*Galeopsis* sp.), are both hosts of *Verticillium*. Both fertility treatments include rotation crops susceptible to *Verticillium*, but their effect on inoculum levels in this case is unknown. The general stress factor present towards the end of the 1994 season was drought. Stress factors specific to the BIO system include high numbers of aphids and, possibly, copper toxicity.

The relative importance of these three factors needs to be assessed.

Treatment	Material	Rate (lb/A)	#	Application Interval	Dates
Conventional	Dithane DF	1.5	7	7	14/7–23/8
	Ridomil MZ	58	2	14	28/7,11/8
Reduced Input	Dithane DF	2.0	7	7	24/7–23/8
	Ridomil MZ	58	1		11/8
Biological	Kocide	2.0	5	10	14/7–23/8
	Ridomil 2E		1		23/8

VI. Economic Results

Michele C. Marra[1]

INTRODUCTION

The "bottom line" may be the most important result to report from a farmer's point of view. Even if a production strategy is much less harmful to the environment, if it does not provide enough net return, then it is not likely to be widely adopted by farmers. While many farmers are willing to give up some profit in exchange for less environmental damage, they still must make enough profit to survive in the long term. Therefore, the economic aspects of any production system are an integral part of its measure of sustainability.

The economic results presented here are compiled from daily logs maintained by the project manager each year in which detailed, plot-level input records were kept. These records were combined with plot-level yields and input and output prices to calculate the economic performance of each plot in each year. Then the plot-level results were averaged over each treatment combination to produce the treatment-level economic performance in each year.

Rather than calculate the total profit of each alternative in each year, we used the return over variable costs as the measure of economic performance. The return over variable costs is calculated by subtracting from total revenue (yield per acre x price per cwt) the sum of all variable production costs. Variable costs are all costs that will be incurred only if production takes place. These costs include seed, fertilizer, pesticides, and field operation costs, but exclude any annualized ownership costs. Ownership costs are those costs the grower will have to pay whether or not he/she decides to produce a crop in any particular year, such as machinery payments, mortgage payments, property taxes, and household expenses. The return over variable cost can be thought of as the annual amount per acre left over after all of the variable factors are paid. This leftover amount can be applied to the ownership costs.

We use this measure (and exclude an estimate of ownership costs) for two reasons. First, ownership costs are quite different among producers, since they have different machinery, equipment, and land values. Therefore, any estimate we would make would not be generalizable. Second, ownership costs should be relatively

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[1] Special thanks go to Ellen Mallory for her meticulous and expert help with the economic data.

constant for an individual grower when comparing production methods. In other words, the land, buildings, machinery, and equipment needed do not change very much regardless of the production method used. Therefore the relative profitability of the treatments can be compared using the return over variable costs. In addition, the results will be applicable to almost any potato producer in the area.

Although we tried to make the economic results presented in this chapter reflective of commercial-scale production methods and costs, readers should use care in viewing them as such. First, the price we paid for potato waste compost likely was higher than it would be were there a nearby commercial market for this input with several suppliers. Since this input has a major effect on the profitability of the amended soil management treatments, breakeven analysis was performed to estimate the compost price that would make the amended treatments equal in profitability to the unamended treatments. The results of this analysis are presented at the end of this chapter. Second, two of the biological pest control materials (*Perillus bioculata* and *Beauveria bassiana*) are still experimental for potato pest control. Nematodes were used during the 1992 crop year only on a trial basis. They were found not to be cost-effective at current prices and were left out of the economic analysis. *Perillus bioculatus*, was applied to the BIO plots several times during the 1993 and 1994 growing seasons at a rate of one per plant (about 16,000/application/A). The production of *Perillus* is limited to laboratory-scale at this time, making even a rough estimate of its commercial cost to producers very difficult. The lowest available estimate of production costs using currently available technology is $0.14 per insect (D. Vacek, Mission Biological Control Center, pers. comm.), which translates to approximately $2200/application/A. At present and for the foreseeable future, the cost would be prohibitive for any potato producer. For this reason, we decided to omit this input and its cost from the profitability measures, as well. *Beauveria bassiana* was used in the BIO plots in each of the last three years. It is a registered product, but at the time of this writing, it is not commercially available. When available, it will cost approximately $20.00/lb, although the cost may be lower (Pauline Woods, Mycotech Bioproducts Inc., pers. comm.). The application rate on the BIO plots has been about 1 lb/A. Since this predator is expected to be available for Colorado potato beetle control sooner than the others and its cost is not as prohibitive, we included this input and its cost in the economic analysis.

INPUT AND FIELD OPERATIONS COSTS USED IN THE STUDY

Table 6.1 contains the input prices that were used in the study by year. We tried to obtain market prices where possible, except for the potato selling price, which was fixed at the ten-year average tablestock price for Maine (USDA). This was done because potato prices are quite variable over time and across end uses and to use market prices would confound the analysis of the returns to the various treatment combinations. The other exceptions to the use of market prices were, as noted above, the price of potato waste compost, nematodes, and *Perillus bioculata*. Notice that the price

Table 6.1 Material prices for potato plots.

Material	Type	unit	1991	1992	1993	1994
Potato selling price		$/cwt	5.50	5.50	5.50	5.50
Atlantic seed price		$/cwt	7.50	10.00	8.50	10.00
Superior seed price		$/cwt	8.00	8.00	7.50	10.50
Diesel Fuel		$/gal	0.98	0.98	0.98	0.61
Compost	A	$/ton	15.00	12.50	15.00	17.82
Manure	A	$/ton	4.60	4.00	4.00	6.09
Dithane DF	F	$/lb	2.20	2.40	3.35	2.70
Ridomil MZ	F	$/lb	9.40	9.55	9.30	9.00
Ridomil 2E	F	$/pt	—[a]	4.60	4.60	—
Kocide	F	$/lb	—	2.76	2.70	3.00
Diquat	H	$/pt	9.38	9.38	8.38	9.97
Sencor DF	H	$/lb	—	25.20	26.00	—
Gramoxone	H	$/pt	—	4.82	3.72	3.99
Lexone	H	$/lb	24.20	—	—	27.14
B.T. Foil	I	$/qt	7.38	9.84	9.84	9.84
Asana	I	$/oz	0.96	1.01	1.00	1.04
Thiodan 2EC	I	$/qt	8.65	—	—	7.70
Rotenone	I	$/pt	5.00	6.54	—	6.33
PBO	I	$/oz	0.80	0.94	0.96	0.96
Monitor	I	$/pt	7.60	7.97	7.88	7.63
Agway Spray	I	$/oz	1.00	—	—	—
Pyrenone	I	$/oz	—	2.00	2.00	1.57
Beauveria bassiana	I	$/lb	—	20.00	20.00	20.00
10-10-10	N	$/lb	0.09	0.09	0.08	0.08
Ammonium Nitrate	N	$/lb	—	0.12	—	0.09
UAN 32%	N	$/lb	0.12	0.12	0.11	0.12
Potassium Chloride	N	$/ton	—	—	—	170.00
X-77	S	$/pt	1.69	1.69	1.69	1.43

A = amendment H = herbicide I = insecticide F = fungicide N = fertilizer S = surfactant

[a] — means that the input was not used in that year.

of diesel fuel remained essentially unchanged through 1993 and then fell by more than 30%.

Table 6.2 lists the per-acre costs of all field operations used in the study by year. These were calculated using standard machinery variable cost procedures, as described in Boehlje and Eidman (1984). The price of skilled and unskilled labor remained steady over the study period. The only component of machinery variable cost that changed substantially was the decrease in the cost of diesel fuel in 1994; operation costs were calculated separately for this year. Plot level information on field operations was adjusted to reflect commercial costs on a per-acre basis based on consultation with experienced farmers in the area.

Variable Cost

Variable costs for each treatment

There are four variety/soil management combinations for each of the three pest management treatments in the study. They are (1) Atlantic, soil amended; (2) Superior, soil amended; (3) Atlantic, soil unamended; (4) Superior, soil unamended. Tables 6.3 and 6.4 show the average (over plots), per-acre variable cost of each pest management treatment on an annual basis, as well as over time, for the amended and unamended treatments, respectively. Because the biological pest management treatment began with the 1992 crop year, both three- and four-year averages were calculated for each treatment combination for overall comparison purposes.

The reduced input (RI) pest management system appears to be the lowest cost of the three, with approximately an $80/A average advantage over the conventional (CONV) pest management system. The cost of the biological (BIO) pest management system

Table 6.2. Potato field operation costs used in the economic analysis.

Field Operation	Unit	1991–1993	1994
Spread	$/A	19.22	17.55
Disk	$/A	6.93	6.59
Spray	$/A	3.85	3.66
Cultivate	$/A	15.39	14.64
Side Dress	$/A	3.85	3.66
Harrow	$/A	5.69	4.83
Plant	$/A	10.70	10.26
Rolling	$/A	1.91	1.81
Roto-Beat	$/A	8.50	7.85
Harvest	$/A	160.00	154.92

Table 6.3. 1991–1994 Return over variable costs for soil amended treatments ($/A).

Potato cultivar Year	Conventional			Reduced Input			Biological		
	Total return	Total variable costs	Return over variable costs	Total return	Total variable costs	Return over variable costs	Total return	Total variable costs	Return over variable costs
Atlantic									
1991	1256.51	865.11	391.40	1081.43	826.87	254.56	—	—	—
1992	1801.94	969.61	832.33	1674.75	843.53	831.22	1108.94	967.63	141.31
1993	1517.04	956.46	560.58	1546.19	898.70	647.49	1549.90	997.48	552.42
1994	1564.34	1057.90	506.44	1629.79	985.10	644.69	1425.74	1168.30	257.44
3-year average	1627.78	994.65	633.12	1616.91	909.11	707.80	1361.53	1044.47	317.06
4-year average	1534.96	962.27	572.69	1483.04	888.55	594.49	—	—	—
Superior									
1991	1271.28	855.01	416.27	890.69	816.77	73.92	—	—	—
1992	1783.65	923.61	860.04	1905.89	797.53	1108.36	1098.08	921.63	176.45
1993	1477.30	913.21	564.09	1363.31	855.44	507.87	1352.86	954.23	398.63
1994	1550.31	1068.40	481.91	1406.21	995.60	410.61	1020.11	1178.80	-158.69
3-year average	1603.75	968.40	635.35	1558.47	882.86	675.61	1157.02	1018.22	138.80
4-year average	1520.64	940.06	580.58	1391.53	866.34	525.19	—	—	—

Table 6.4. 1991—1994 Return over variable costs for soil unamended treatments ($/A).

	Conventional			Reduced Input			Biological		
Potato cultivar Year	Total return	Total variable costs	Return over variable costs	Total return	Total variable costs	Return over variable costs	Total return	Total variable costs	Return over variable costs
Atlantic									
1991	1484.06	694.17	789.89	965.05	655.93	309.12	—	—	—
1992	1709.95	775.67	934.28	1740.06	649.59	1090.47	951.36	710.16	241.20
1993	1449.39	727.34	722.05	1419.28	678.26	741.02	1452.96	729.04	723.92
1994	1490.78	819.98	670.79	1474.13	761.82	712.31	1031.39	945.02	86.37
3-year average	1550.04	774.33	775.71	1544.49	696.56	847.93	1145.24	794.74	350.49
4-year average	1533.55	754.29	779.26	1399.63	686.40	713.23	—	—	—
Superior									
1991	1114.50	684.07	430.43	802.75	645.83	156.92	—	—	—
1992	1694.28	729.67	964.61	1817.20	603.59	1213.61	962.50	664.16	298.34
1993	1343.51	684.09	659.42	1303.78	635.01	668.77	1189.65	685.79	503.86
1994	1375.29	830.48	544.80	1444.02	772.32	671.70	835.59	955.52	-119.93
3-year average	1471.03	748.08	722.94	1521.67	670.31	851.36	995.91	768.49	227.42
4-year average	1381.89	732.08	649.82	1341.94	664.19	677.75	—	—	—

ranges from \$664/A in the 1992 unamended Superior plots to \$1179/A in the 1994 amended Superior plots. The range of costs for the CONV system is from \$684/A in the 1991 and 1994 unamended Superior plots to \$1058/A in the 1994 amended Atlantic plots. In some years, the CONV system cost more than the BIO system and in some years the reverse was true. Overall, however, the costs of these two treatments were similar when compared within soil management systems. As was discussed previously, the amended soil management system resulted in higher cost in all pest management systems than the unamended system.

Cost shares

To compare the three pest management systems in terms of relative input use, we divided the variable costs into five categories: seed, compost and manure, chemical fertilizer, field operations, and pesticides. Tables 6.5 through 6.10 show the variable costs by category for each treatment combination and year, as well as the overall averages. Figures 6.1 through 6.6 depict the overall three-year average share of each input category in total variable cost, so that visual comparisons can be made more easily. As expected, the cost of compost and manure dominates the amended treatments. The cost share of pesticides is lowest in the RI system and about the same in the CONV and BIO systems when compared within soil management systems. It is clear that the RI system results in less pesticide loading in the environment than the CONV system. Although the cost shares of pesticides are similar in the CONV and BIO systems, the BIO system should result in less total material applied (because BIO pesticides are generally more expensive than CONV) and less toxic material being introduced into the environment. These figures show also the reduced share (by about half) of chemical fertilizer cost in the amended soil management system compared to the unamended soil management system.

Return over Variable Cost

As was mentioned earlier, the return over variable cost gives a measure of the amount of income left over to pay for the ownership costs and provide a normal return for the producer. Therefore, a treatment combination that results in a return over variable cost greater than zero does not mean necessarily that it is profitable. The producer would have to subtract an estimate of ownership costs per acre from the return over variable cost to estimate the total profitability of a treatment combination. The return over variable cost does, however, provide a good measure of the relative profitability of the treatment combinations.

Table 6.5. The cost of seed, compost and manure, chemical fertilizer, pesticides and field operations for 1991–1994: conventional, soil amended ($/A).

Year	Seed	Compost and Manure	Chemical Fertilizer	Pesticides	Field Operations	Total Variable Costs
Atlantic						
1991	172.50	182.00	60.75	121.10	328.76	865.11
1992	230.00	205.00	60.38	147.38	326.85	969.61
1993	195.50	230.00	63.47	140.29	327.20	956.46
1994	210.01	300.00	48.00	172.92	326.97	1057.90
Superior						
1991	162.40	182.00	60.75	121.10	328.76	855.01
1992	184.00	205.00	60.38	147.38	326.85	923.61
1993	152.25	230.00	63.47	140.29	327.20	913.21
1994	220.51	300.00	48.00	172.92	326.97	1068.40
3-Year Average	198.71	245.00	57.28	153.53	327.01	981.53
4-Year Average	190.90	229.25	58.15	145.42	327.45	951.16

Table 6.6. The cost of seed, compost and manure, chemical fertilizer, pesticides and field operations for 1991–1994: reduced input, soil amended ($/A).

Year	Seed	Compost and Manure	Chemical Fertilizer	Pesticides	Field Operations	Total Variable Costs
Atlantic						
1991	172.50	182.00	60.75	94.42	317.20	826.87
1992	230.00	205.00	60.38	35.78	312.37	843.53
1993	195.50	230.00	59.60	99.87	313.73	898.70
1994	210.01	300.00	48.00	103.78	323.31	985.10
Superior						
1991	162.40	182.00	60.75	94.42	317.20	816.77
1992	184.00	205.00	60.38	35.78	312.37	797.53
1993	152.25	230.00	59.60	99.87	313.73	855.44
1994	220.51	300.00	48.00	103.78	323.31	995.60
3-Year Average	198.71	245.00	55.99	79.81	316.47	895.99
4-Year Average	190.90	229.25	57.18	83.46	316.65	877.45

Table 6.7. The cost of seed, compost and manure, chemical fertilizer, pesticides and field operations for 1991–1994: biological, soil amended ($/A).

Year	Seed	Compost and Manure	Chemical Fertilizer	Pesticides	Field Operations	Total Variable Costs
Atlantic						
1991	—	—	—	—	—	—
1992	230.00	245.00	0.00	162.11	330.51	967.63
1993	195.50	230.00	15.47	217.92	338.60	997.48
1994	210.01	300.00	48.00	277.28	333.01	1168.30
Superior						
1991	—	—	—	—	—	—
1992	184.00	245.00	0.00	162.11	330.51	921.63
1993	152.25	230.00	15.47	217.92	338.60	954.23
1994	220.51	300.00	48.00	277.28	333.01	1178.80
3-Year Average	198.71	258.33	21.16	219.10	334.04	1031.35
4-Year Average	—	—	—	—	—	—

Table 6.8. The cost of seed, compost and manure, chemical fertilizer, pesticides and field operations for 1991–1994: conventional, soil unamended ($/A).

Year	Seed	Compost and Manure	Chemical Fertilizer	Pesticides	Field Operations	Total Variable Costs
Atlantic						
1991	172.50	0.00	110.25	121.10	290.32	694.17
1992	230.00	0.00	109.88	147.38	288.41	775.67
1993	195.50	0.00	107.60	140.29	283.95	727.34
1994	210.01	0.00	123.97	172.92	313.08	819.98
Superior						
1991	162.40	0.00	110.25	121.10	290.32	684.07
1992	184.00	0.00	109.88	147.38	288.41	729.67
1993	152.25	0.00	107.60	140.29	283.95	684.09
1994	220.51	0.00	123.97	172.92	313.08	830.48
3-Year Average	198.71	0.00	113.82	153.53	295.15	761.21
4-Year Average	190.90	0.00	112.93	145.42	293.94	743.19

Table 6.9. The cost of seed, compost and manure, chemical fertilizer, pesticides and field operations for 1991–1994: reduced input, soil unamended ($/A).

Year	Seed	Compost and Manure	Chemical Fertilizer	Pesticides	Field Operations	Total Variable Costs
Atlantic						
1991	172.50	0.00	110.25	94.42	278.76	655.93
1992	230.00	0.00	109.88	35.78	273.93	649.59
1993	195.50	0.00	107.60	99.87	275.29	678.26
1994	210.01	0.00	123.97	103.78	324.06	761.82
Superior						
1991	162.40	0.00	110.25	94.42	278.76	645.83
1992	184.00	0.00	109.88	35.78	273.93	603.59
1993	152.25	0.00	107.60	99.87	275.29	635.01
1994	220.51	0.00	123.97	103.78	324.06	772.32
3-Year Average	198.71	0.00	113.82	79.81	291.09	683.43
4-Year Average	190.90	0.00	112.93	83.46	288.01	675.30

Table 6.10. The cost of seed, compost and manure, chemical fertilizer, pesticides and field operations for 1991–1994: biological, soil unamended ($/A).

Year	Seed	Compost and Manure	Chemical Fertilizer	Pesticides	Field Operations	Total Variable Costs
Atlantic						
1991	—	—	—	—	—	—
1992	230.00	0.00	22.13	162.11	295.99	710.16
1993	195.50	0.00	15.47	217.92	300.16	729.04
1994	210.00	0.00	123.97	277.28	333.76	945.02
Superior						
1991	—	—	—	—	—	—
1992	184.00	0.00	22.13	162.11	295.92	664.16
1993	152.25	0.00	15.47	217.92	300.16	685.79
1994	220.51	0.00	123.97	277.28	333.76	955.52
3-Year Average	198.71	0.00	53.86	219.10	309.95	781.62
4-Year Average	—	—	—	—	—	—

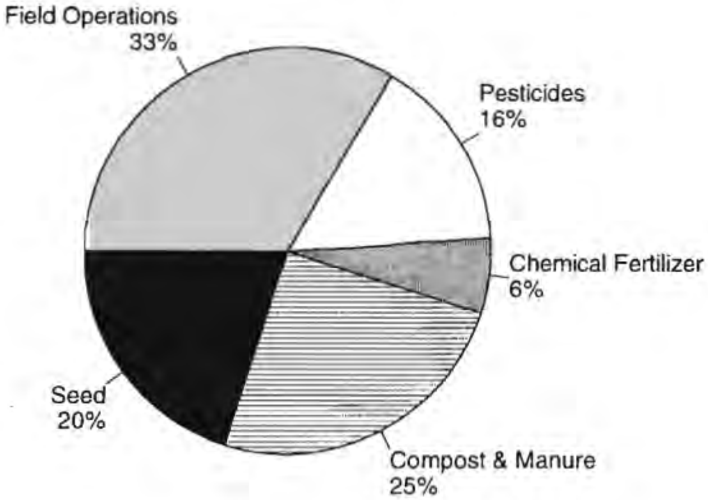

Figure 6.1. 1991–1994 average input shares of variable cost: conventional, soil amended.

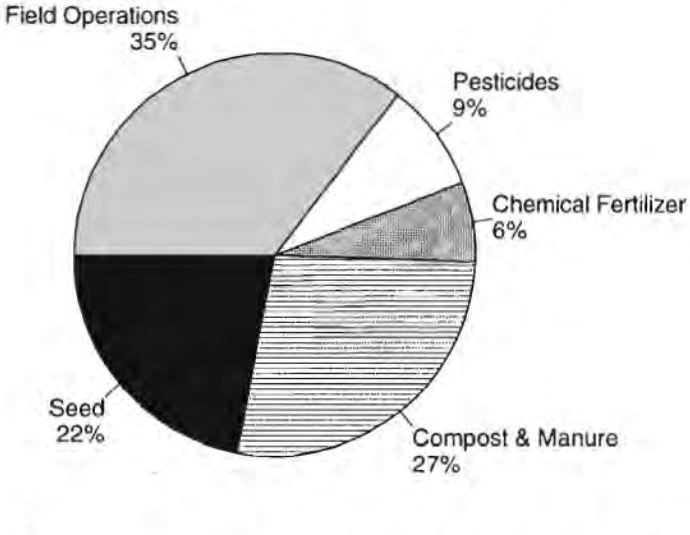

Figure 6.2. 1991–1994 average input shares of variable cost: reduced input, soil amended.

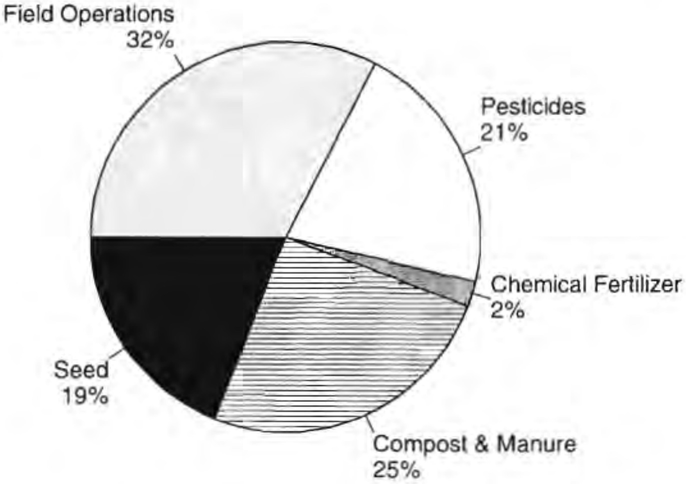

Figure 6.3. 1991–1994 average input shares of variable cost: biological, soil amended.

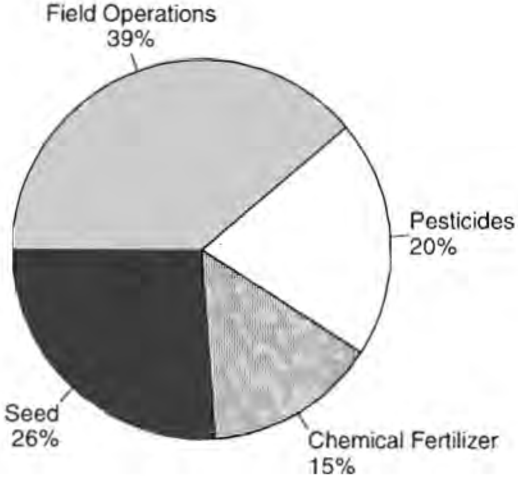

Figure 6.4. 1991–1994 average input shares of variable cost: conventional, soil unamended.

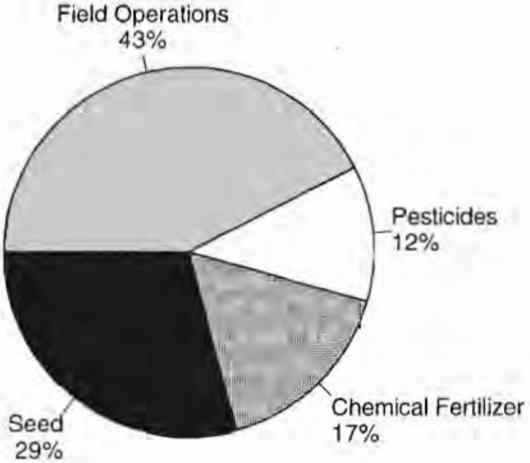

Figure 6.5. 1991–1994 average input shares of variable cost: reduced input, soil unamended.

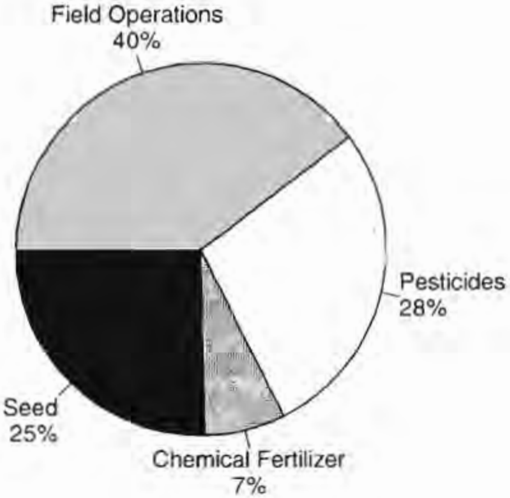

Figure 6.6. 1991–1994 average input shares of variable cost: biological, soil unamended.

Tables 6.3 and 6.4 show the returns over variable cost for each treatment combination. Comparing the most recent three-year averages, the RI system showed highest returns over variable cost for each variety/soil management combination, with a profit advantage of between $40 and $130 per acre over the CONV system. The BIO system resulted in the lowest average return over variable cost for each variety/soil management combination, and for Superior in 1994, there were negative returns over variable cost in the BIO plots for both soil management systems. Comparison of the CONV and RI systems over the four years shows the RI system averaged higher profit than CONV in the amended Atlantic plots (by about $20/A) and in the unamended Superior plots (by about $30/A). The CONV system was more profitable in the amended Superior plots (by about $55/A) and in the unamended Atlantic plots (by about $65/A). These results are very encouraging when the difference in environmental impact between the CONV and RI systems is considered.

Rotation Crops

In 1992 the green manure rotation crop was used in the BIO pest management system only. Barley was used as the rotation crop in the other two pest management systems. Beginning in 1993, however, the green manure rotation was coupled with all plots receiving soil amendments, regardless of pest management system. This was done so we could begin to examine the effects of a longer-term, intensive effort to build up the soil. We recognized that this would result in some short-term economic losses, but viewed them as a potential initial investment that would pay future dividends in terms of crop health, yield, and net returns. It is too soon to tell how much difference this strategy will make, but we can begin to quantify the initial investment required in terms of production costs and foregone income from a marketable rotation crop such as barley. Table 6.11 contains the variable production costs and returns over variable cost for the rotation crops by year. The additional investment required in 1993 was about $300.00/A and about $150.00/A in 1994 (the decrease attributable primarily to the decision not to apply compost beginning in 1994 to these plots). It will be a few years before we can begin to measure the return on that investment.

As with compost, the costs of the components of the green manure crop may be inflated over what would be encountered on a farm. In particular, the price and seeding rate for peas are likely higher than they would have been in a commercial operation. Pea

Table 6.11. Barley and green manure variable costs and return over variable cost by year and treatment[a].

	Year	Treatment	Variable Cost	Return Over Variable Cost
			$/A	$/A
Barley				
	1992	CONV, amended	262.67	-146.92
	1992	CONV, unamended	111.50	6.55
	1992	RI, amended	262.14	-145.73
	1992	RI, unamended	110.96	-3.67
	1993	CONV, unamended	127.48	-29.80
	1993	RI, unamended	127.04	-28.22
	1993	BIO, unamended	122.75	-22.41
	1994	CONV, unamended	155.51	-41.16
	1994	RI, unamended	155.10	-26.78
	1994	BIO, unamended	151.03	-43.53
Green Manure				
	1992	BIO, amended	267.56	-267.56
	1992	BIO, unamended	116.35	-116.35
	1993	All	292.33	-292.33
	1994	All	143.77	-143.77

[a] Averaged over plots containing both potato varieties the previous crop year.

seed was ordered from a firm in Washington State and was subject to high transport costs. If the green manure rotation strategy turns out to produce net benefits, then a market for the components of it would likely emerge nearby, thus reducing the transport cost part of the price. Also, through a component study, we discovered that the seeding rate for peas in the green manure crop was higher than it needed to be to achieve the same level of benefit (Jannink et al. in press). In future years, the pea seeding rate and, thus, the production costs of the green manure crop will be lower, which will increase the profitability of the green manure rotation relative to the barley.

Breakeven Compost Price

If the amended soil management system is too costly relative to the unamended system, then it is less likely that producers will adopt it. The price of potato waste compost used in the amendment treatments is suspected of being higher than a true market price, since there is only one supplier in the area. If more suppliers were competing, then the price of compost should be lower, It is impos-

Table 6.12. Fertilization cost components for each soil management treatment[a].

	Soil Amended			Soil Unamended		
Input	Amt/A	Price/Unit	Cost/A	Amt/A	Price/Unit	Cost/A
10-10-10	600 lb	$ 0.08	$48.00	1200 lb.	$ 0.08	$96.00
Spread	1	17.55	17.55	1	17.55	17.55
Ammonium Nitrate	—	—	—	150 lb	0.09	13.50
Sidedress	—	—	—	1	3.66	3.66
Compost	10 tons	17.82	170.82	—	—	—
Spread	1	17.55	17.55	—	—	—
Manure	20 tons	6.09	121.80	—	—	—
Spread	1	17.55	17.55	—	—	—
Disk	1	6.59	6.59	—	—	—
Subtotal (potato year)			$399.86			$148.26
Rotation Crop (net cost)			143.77			37.16
Total (2 years, 1 rotation cycle)			$543.63			$185.42

[a] All amounts and prices are 1994 levels.

sible, however, to predict how much lower with current market information, but it is possible to calculate the compost price that would make the total cost of the two soil management systems equal.

If the total costs of the two soil management methods were the same, then we would expect producers to choose the organic amendments over the chemical fertilizer (assuming they result in the same soil fertility in the current crop year and the organic amendments improve soil tilth over time). The compost price that results in equal total costs is called the breakeven price.[2] To calculate it, the cost components of each soil management system are listed separately (Table 6.12). Then the breakeven price of compost is calculated from solving the equation: NC + ComX = TCU for X, where NC is the total of all the non-compost costs in the soil amended fertilization regime, Com is the amount of compost applied per acre, X is the breakeven price of compost, and TCU is the total fertilization cost of the unamended treatments. The breakeven price with all other values held at the levels shown in Table 6.12 is $-9.79/ton! This means that the producer would have

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[2] The breakeven prices calculated here compare only the fertilization methods in the potato year and ignore the choice of rotation crop.

to be paid to use the compost in order to break even between the two soil management systems. This price was calculated under several simplifying assumptions, however. For instance, in many cases, manure is a waste product from another farm enterprise and may not have to be purchased if there is an excess supply.[3] If the price of manure is assumed to be zero, the breakeven price of compost becomes $2.39/ton.

Another assumption made in the first breakeven price calculation is that the soil amendments will not improve yield in the future. This is contrary to our expectations. As an example of how future yield increases would change the breakeven price of compost, assume that the soil amendments would improve yield by 5 cwt/A in each of the next five years. The value of this yield improvement, discounted at 5% and assuming a potato price of $5.50/cwt, is $345.56. If we consider that additional value as a cost (in terms of foregone revenue) of using the unamended management system, the breakeven price of compost becomes $24.78/ton, higher than the actual price was in 1994. Keep in mind that this is an extreme example used to illustrate how yield improvement might affect the breakeven price. We cannot estimate with any accuracy the yield improvement at this time, although the trend is emerging. When the future yield effects of the soil amendments are known, the breakeven price can be estimated more realistically.

Reality Check

We do not suggest that the economic results reported here are those that any particular grower could obtain using one of the production methods. We are, however, confident that the relative returns over variable cost would be applicable at the individual producer level. As a check to see if the magnitudes of the results obtained in the study so far reflect commercial-scale potato production, we compared the range of the returns over variable costs for five years for Farm Credit Association Borrowers reported in Potato Farm Summary, adjusted to 1992 dollars, with the range of results in the study. The Farm Credit farmers' returns over variable cost ranged from $469 to $1238 per acre. The range in this study is from $390 to $964 per acre for CONV production, which seems to be acceptably comparable to commercial results.

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[3] Just because it is produced on the farm as a waste product does not necessarily imply an input has a zero price. If there is a market for the input, then the cost of using it on the farm is its value in the marketplace.

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VII. Ecological Interactions

Francis A. Drummond, Matt Liebman, and Michele C. Marra

In previous chapters, the effects of potato variety, soil management, and pest management systems on soil characteristics, plant growth and yield, and pest populations have been discussed in detail, but from individual disciplinary perspectives. In this chapter, we will summarize and integrate these effects into a more ecological or holistic framework. One way to do this is to construct a conceptual model, such as that shown in Figure 7.1, which depicts the relationships between the biotic and abiotic components of the potato ecosystem. Included in the figure are interactions that we measured in the large-scale potato ecosystem study, those measured in smaller scale companion component studies, and those reported previously in the literature that we judged to be applicable to Maine.

The heavy black arrows in Figure 7.1 represent our initial general hypotheses about potato management systems and their effects on the soil environment, the potato plant, the pests of potato, and natural enemies of the pests. (Positive interactions are depicted with solid lines; negative interactions are depicted with dashed lines.) These hypotheses coincide with the experimental design of the research project. For instance, arrows leading from the soil management component to the soil environment and potato plant components represent our hypotheses that use of soil amendments and green manure rotation crops would improve soil fertility, potato growth, and yield. The pest management systems were hypothesized to reduce pest populations, while having neutral to negative effects on the pest natural enemy populations. The reasoning behind this is that most pest management tactics that directly reduce pest densities will also have a deleterious effect on natural enemies through directly toxic effects, as well as a reduction in prey (pests) that results in less food for the natural enemies. The thick gray, thin gray, and thin black arrows illustrate our findings with respect to specific ecological interactions that we measured in the ecosystem experiment, measured in ancillary component studies, or that have been reported by other researchers, respectively.

We have arranged the components of the potato ecosystem hierarchically. As an example, the soil environment is a component of the ecosystem, but it also contains subcomponents, such as soil organic matter, micronutrients, macronutrients, cation exchange

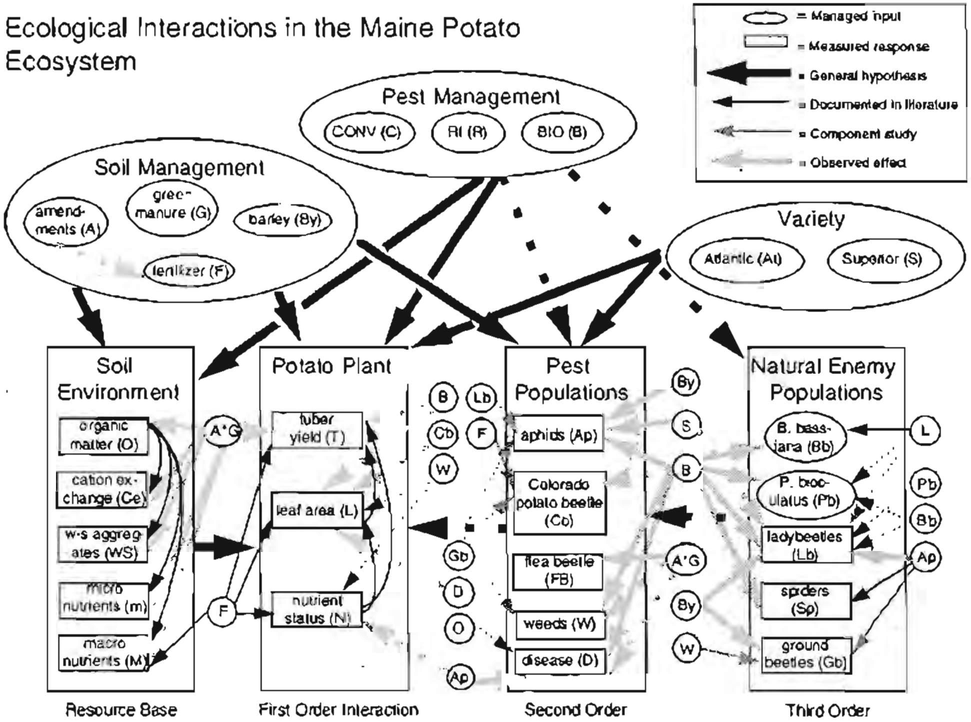

Figure 7.1. A conceptual model of ecological interactions in the potato ecosystem. To interpret depicted relationships, trace arrow from base to point. If one increases component at its base and the result is an increase in the component at point, then a positive relationship exists (solid line). If a decrease occurs in the component at its point, then a negative relationship exists (dashed line). The exception is with qualitative components such as pest management systems. In this case the comparison is relative to the other categories of component (e.g., biological, conventional, or reduced input). Thus a decrease in yield due to the biological system is only relative to the other pest management systems.

characteristics, and water-stable aggregates. Within each of these subcomponents may be many sub-subcomponents.

Many components of the potato ecosystem, such as the soil microbial community, were not examined in this study. Therefore, it is important to keep in mind that the conceptual model we are presenting is an incomplete one. The choice of the components to include in our study was based upon three factors: components hypothesized to have especially important and measurable responses to our imposed treatments (large ovals representing the management strategies), components that could be measured with the financial resources available, and components that fell within the areas of expertise of our scientific investigators.

Other hierarchies exist in the conceptual model. First there is the division between managed inputs in the ecosystem and the response variables. The managed inputs are those components (large ovals) that we manipulated and imposed as the management treatments: soil management treatments, variety choice, and pest management systems. The response variables (depicted as rectangles) are the biological organisms and physical entities that respond to the managed inputs and to each other. Both types of components interact and define the potato ecosystem. Our conceptual model does not include the myriad of uncontrolled inputs such as air temperature, rainfall, or solar radiation. These inputs are very important in driving many ecological interactions. For the purposes of our discussion, however, we have omitted them because they are less likely to be affected by management systems.

Another hierarchy represented in our conceptual model is the ordering of the interactions. This ordering arises from our research objectives; a different set of researchers with another set of objectives might have had a different ordering. One of our primary foci was on soil and nutrient dynamics and how these dynamics affected potato growth and development, pest management, and pest dynamics. Therefore, we used the soil environment and resource base as a reference point. The first level of interactions involved directly with the resource base are those contained in the potato plant component. The second level of interactions (those removed one level from the resource base) are those components involved directly with the pests of the potato plant. The third level of interactions still can affect the soil environment, but only indirectly since they interact directly with the pest components. These are the natural enemy components. This ordering can be useful in illustrating direct and indirect effects between components in the potato ecosystem.

We partitioned the types of interactions into those we measured in the ecosystem large-scale study (thick gray), those we measured in ancillary component studies (thin gray), and those reported in the scientific literature (thin black). For instance, we found that soils in potato plots that received amendments and green manure increased in organic matter (A*G-O). We found in a component study that increased fertilization affects the potato plant response to Colorado potato beetle feeding (Mena-Covarrubias 1995). Scientific literature (Russell 1980) has already documented that an increase in soil organic matter can increase soil cation exchange capacity (O-Ce).

Figure 7.1 includes positive (solid lines) and negative interactions (dashed lines). An example of a positive interaction is our finding that an increase in the use of soil amendments and green manure results in an increase in soil macronutrients (A*G-M). A negative interaction can be described as follows: an increase in the level of one factor or component results in a decrease in the level or existence of another factor or component. An example of a negative interaction in the potato ecosystem is the effect of ground beetles on weeds (G-W). In one component study, Zhang (1993) showed that the adult ground beetle *Harpalus rufipes* feeds on weed seeds in potato and barley fields, resulting in as much as a 70% reduction in experimentally sown weed seed densities. An increase in *H. rufipes* numbers, therefore, should cause a decrease in the weed seed bank. Another negative effect is our finding that a decrease in nitrogen status of the potato plant accompanies an increase in aphid density (Ap-N).

Although we now understand much more about the chemical, physical, and biological relationships within the potato ecosystem, we have measured only a few of the many interactions. We do not know the effect of changing production practices on ground- and surface water, air quality, or pesticide residues on the marketed potato crop. Costs of production of potato and rotation crops are only part of the total costs to society. The other costs to society derive from "spillovers" or externalities. For instance, a toxic material leaching into the groundwater can not only affect the health of the farm family members, but can also affect the health of other community members.

External costs, although more difficult to measure, are as economically legitimate as the cost of potato seed, for example. When taken together, the two cost categories constitute the total social cost of the farm production. Figure 7.2 is an extension of Figure 7.1 and illustrates the economic relationships (direct and

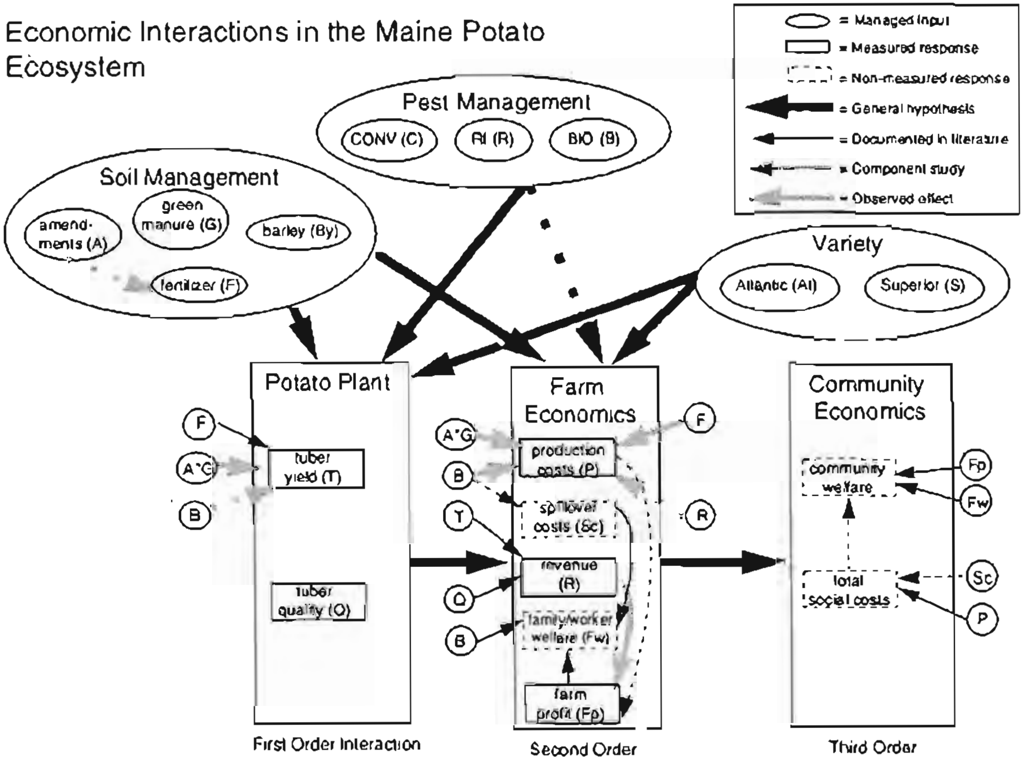

Figure 7.2. A conceptual model of economic interactions in the potato ecosystem (for an interpretation of the relationships depicted see Figure 7.1 and text).

spillovers) we have quantified from the study results (thick gray arrows) and those that can be derived from established literature (thin black arrows).

It is becoming clear from the experimental results that the choice of variety, pest management system, and soil management system will affect farm profit and thus, the welfare of the farm family, farm workers, and farm community. If profit is higher, then all groups may experience increases in their general welfare (if profits are equitably distributed). The reduced input (RI) pest management system has consistently been the highest profit option. Although the spillover costs are not known for this system, clearly they are less than those associated with the conventional (CONV) pest management system, since lower levels of toxic materials are applied. It is not clear, however, whether the RI or the biological (BIO) pest management system is preferred by the broader community. The social costs of the RI system may or may not outweigh the higher farm profit in the RI system compared with the BIO system.

The same is true with respect to choice of soil management system. We know much more about the effect of this choice on production costs, yield, and profit than we know about the external effects. Until we begin to measure the extent of the spillovers, our knowledge of the potato ecosystem in this context remains limited.

For many readers, Figures 7.1 and 7.2 might appear, at first glance, too complicated to be helpful in understanding the ecological interactions that characterize the northern Maine potato ecosystem. However, the conceptual model quickly leads one to appreciate at least two important points: (1) the potato ecosystem is made up of many linked (interacting) components, and (2) these linkages connect components through the hierarchies of the ecological energy web (resource base to first order interactions to second order interactions). This is important because it implies that if one perturbs, or changes the magnitude of, one component in a specific hierarchical level, then a "ripple effect" may occur. This ripple may result in changes in the magnitude of a component in another hierarchical level. Based upon our conceptual model, a change in the amount of soil amendment not only results in a change in soil organic matter (a within-hierarchy dynamic), but also may result in a direct change in tuber yield (a single order ripple), a change in weed abundance and species composition (a second order ripple), and as a result, a change in ground beetle weed seed predator abundance (a third order ripple). Multiple interactions and dynamic feedback in the potato ecosystem, however, may dampen the ripple effect as it moves through the ecological hierarchy.

It is the goal of the potato ecosystem project to predict these effects, especially when they are results of management systems. Thus an objective of our research is to quantify the important interactions (see below) that may be driving the ecology of the potato ecosystem. This process involves four steps.

The first step entails identifying those key effects and interactions present in the system. The key findings (more than two out of four years unless otherwise stated) that we measured in the potato ecosystem study (represented in our conceptual model, Figure 7.1) are as follows.

Soil amendment and green manure effects

1. Use of soil amendments and green manure increased soil organic matter, soil cation exchange capacity, water stable aggregates, and levels of potassium, calcium, magnesium, and boron.
2. Use of soil amendments and green manure increased nutrient uptake and plant biomass production.
3. Use of soil amendments and green manure increased yields and decreased the need for synthetic fertilizer.
4. Use of soil amendments and green manure was too expensive to be profitable at current prices.

Variety effects

1. Aphid numbers were higher on Superior compared with Atlantic.
2. Rhizoctonia disease severity was greater in Superior than in Atlantic (in 1993 and 1994).

Pest management effects

1. The BIO system resulted in lower densities of the Colorado potato beetle compared with the RI and CONV systems.
2. A carry-over effect between years in control of the Colorado potato beetle was seen only in the BIO plots.
3. Flea beetle adults occurred at higher densities (in three out of four years) in the BIO plots treated with soil amendments and green manure.
4. The BIO system had higher numbers of ladybeetle adults relative to the RI and CONV systems, but it also had higher numbers of aphids than the RI and CONV systems.

5. The BIO system resulted in higher levels of foliar late blight relative to the RI and CONV systems, but no difference was found in tuber blight (only one year's data). Higher levels of potato plant early senescence were found in the BIO system relative to the RI and CONV systems (only one year's data), but no difference in early blight occurred between pest management treatments (only one year's data).
6. The BIO system resulted in high levels of copper on potato foliage.
7. Full rates of herbicides may not have been necessary to manage weeds adequately in the potato crop. In 1993 and 1994, weed biomass did not differ between the RI system, which received half rates of herbicides, and the CONV system, which received full rates. In 1994, when potato followed the green manure crop and received soil amendments, weed biomass was similar in all three pest management systems, including the BIO system, which was not sprayed with herbicides.
8. Between 1991 and 1994, weed seed density increased in all pest management systems. The increase was smaller in the CONV system than in the RI and BIO systems. By 1994, weed seed densities were affected by a complex relationship between pest management system, rotation entry point, and soil management system.
9. The BIO system often resulted in lower yields relative to the RI and CONV systems.
10. Profits tended to be highest in the RI system; the BIO system is presently expensive to use.

A second step in understanding the ecological dynamics affecting potato production involves noting areas that may be important, but that are not receiving adequate research effort. This analysis is critical in determining future research priorities. For instance, the conceptual model indicates that we have not addressed the soil microbial community as a component of the soil environment. It is widely believed that an understanding of the soil microbial community and associated soil transformations is key to understanding the dynamics of soil and nutrient management in agroecosystems (Paul and Clark 1989).

The third step in an ecosystem analysis is to identify the causal relationships for the identified interactions. However, the cause-and-effect relationship of some interactions can not always be determined from an initial experiment. For instance in our study, the relationship between aphid density and petiole nitrogen could be due to aphids causing a decrease in nitrogen content of the petioles (this is what we hypothesize to be the case and would reflect a loss of plant nutrients due to aphid feeding). But, the relationship could also be due to aphids exhibiting a preference for plants that are deficient in nitrogen, in which case the plant nitrogen level would determine the aphid density. A specific experiment can be designed to determine the nature of causality in this relationship. This level of experimentation is often referred to as determining the mechanisms of ecological interactions and is the primary focus of our short-term component studies (see Appendix B).

The fourth step in the analysis of ecosystems is to identify feedback dynamics. Feedback dynamics govern the stability or evolution and change of ecosystems. Therefore, until feedback relationships are identified and quantified little prediction about change in the ecosystem can take place. Feedback dynamics are usually classified as one of two types: negative feedback and positive feedback. Negative feedback is defined as a self-restoring process. Negative feedback loops seek to maintain the status quo. They resist change. The term "negative" refers to the fact that this loop negates disturbances. A simple negative feedback loop between two components involves an initial change in one component, which generates a counter change in the other component, which in turn causes the first component to return to its original state. An example of this in the potato ecosystem is the relationship between soil fertility due to the addition of amendments and the use of synthetic fertilizer. The more that soil amendments are used (either frequency or level) the higher the residual soil nitrogen content becomes and consequently less synthetic nitrogen will be needed to supplement the potato plant's nitrogen requirements. This is, however, a very simplistic example and many other factors and relationships would affect this feedback loop (e.g., the effect of soil amendments on soil-borne potato pathogens, the economics of using soil amendments vs synthetic fertilizer).

The antipode of negative feedback is positive feedback, which connotes lack of control or the "vicious cycle," and is not a desirable feature of a managed agroecosystem. An example of a positive feedback loop is the relationship between weeds and potato leaf area. If the potato crop fails to produce a full, vigorous canopy, the resulting availability of light may lead to an increase in weed growth. Increased weed growth will lead to usurpation of more resources and further suppression of potato growth. Obviously, this can lead to a vicious cycle and result in crop loss if unchecked by management systems. Identification of these feedback loops is useful as conceptual models are developed for everyday decision making in potato production. Even a few dynamic feedback loops operating simultaneously, however, can make it difficult to predict a system using a conceptual model. Therefore, we have begun constructing computer simulation models, which incorporate numerous feedbacks (see the "Future" section in Chapter 4). These models will help us answer (in the case of a weed seed bank model, for example) questions such as "what is the best strategy for combining rotation crops and tillage to reduce the weed seed bank?" Our research with simulation models has just begun.

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VIII. The Future

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RESEARCH AND DEMONSTRATION PLANS

Most of this publication is devoted to showing the reader where we have been the past five years. It seems appropriate to conclude the publication with a discussion of where we intend to go from here and why, and with a reflection on the lessons learned so far. Some things about the future of the project are obvious and, in some ways, overriding, with the long- term commitment to experimental continuity being perhaps the most important of these.

There are several reasons why the knowledge gained from a long-term, continuous study is greater than the sum of the benefits from the typical two- or three-year studies. First, weather and other factors beyond the researchers' control can be so fickle that each field season is sometimes akin to a different experiment. It is difficult to have confidence in any conclusions under those circumstances. With a longer study period, the uncontrollable factors "average out," and the true experimental effects emerge. Also, several years are necessary to determine equilibrium positions for pest, beneficial, and pathogen populations. These cycles occur differently over time, so several cycles must be observed to get an accurate understanding. Finally, the full effect of some changes in the cropping system is not realized for several seasons, so system stability cannot be evaluated within a short study period. It is important to observe this transition period and beyond so that the benefits and costs of moving from one system to another can be quantified. Since farmers view this transition period as an investment in the new technique with its associated costs, the economic implications of this period are important for farmers' decision-making process.

As we learn more about the potato ecosystem over time, more research questions will arise, and additional treatments may be necessary. These will be based on component study and mainplot study results, in addition to expansions of the cropping strategies studied. These additions will be decided upon by the research group in consultation with industry representatives and other interested groups.

The research group, itself, is expected to grow and change over time as the need for new expertise, the level of funding, and the growing interest in the project prescribe. For example, recently an agricultural policy analyst and an extension farm management specialist have joined the group. The expertise in soil science in the project is expanding, and that need will become more critical as off-site effects are monitored and evaluated.

We are ready to begin disseminating what we have learned so far. We are planning to increase the involvement of extension personnel and to increase researcher participation in grower meetings. Field days and workshops will become more important. It is also time to demonstrate what we believe to be a more sustainable production system on a commercial scale. Plans are underway to set up this type of demonstration farm in Aroostook County. We would also like to set up demonstrations in central and southern Maine if we find adequate funding and land.

Although organic production is not the focus of the project, several study results may be useful to organic producers. We intend to identify those links and strategies that will fit organic production requirements and standards and to make them available to that segment of the potato industry.

A MODEL FOR FUTURE RESEARCH AND EDUCATION

Beginning in the 1980s and continuing today, Experiment Station scientists have been hired at the University of Maine (UM) with educational backgrounds and experience in ecology and ecosystem-level research. These staff changes have hastened the shift to multidisciplinary research teams, which allow for more comprehensive and intensive examination of commodity production. This shift in personnel philosophy has had significant impacts on agricultural research. The program developments that now occur combine sustainable agricultural practices and environmental science with the traditional agricultural disciplines.

There has been a similar trend in the education mission of land grant universities nationwide. This trend can be seen in the phenomenal growth in ecology, environmental sciences, and natural resources majors that has taken place over the past decade. In the UM College of Natural Resources, Forestry and Agriculture (NFA), one of the largest undergraduate majors is Natural Resources, which attracts students interested in resource management and policy. A new graduate program in Ecology and Environmental Sciences, which has faculty from three UM colleges (NFA, Sciences, and Engineering), has been formed to better coordinate research efforts with student interests and job markets.

Most of the participating potato ecosystem faculty members have recently become members of a new department, Applied

Ecology and Environmental Sciences, a merger of the former Department of Entomology and Department of Plant, Soil and Environmental Sciences. This merger reflects the multidisciplinary evolution of universities by formally associating the component applied sciences. Similar structural changes have occurred in several universities around the country. Now, students are educated broadly and can gain desired research experience within the same department with faculty who are jointly teaching and conducting research at the systems level.

The nature of the potato ecosystem project is such that it embraces the changing student body and university structure. The project has attracted many undergraduates as summer employees, and graduate students have found that the project meets their own professional development goals. The faculty members have identified common interests, developed research approaches that satisfy the needs of each, and shared the resources necessary to accomplish the projects' objectives. In sum, the potato ecosystem project has shown the principles and advantages of cooperative, ecosystem-level research, and thus serves as a model for agricultural education and research for the future.

PERSONAL EFFECTS

As a direct result of the nature of this project, there have been noticeable changes in many study participants. We began as mostly a disparate group of disciplinary researchers with reductionist leanings, but we are learning to speak a common language and to interact as parts of a whole. The struggles to reach consensus and to develop research plans were difficult in the early years. At first, a few truly doubted that significant progress toward sustainability could be achieved. Through the patience and foresight of some and the willingness of many to keep an open mind and to occasionally suspend disbelief, the doubts have been dispelled, and enthusiasm for the project has grown.

Perhaps the most important lesson we have learned from the project is not a research result or scientific discovery. It is, however, as fundamental to successful research as is the proper equipment and personnel: the value of dialogue cannot be underestimated. Dialogue is not accomplished through "educating the public" or a chauvinistic disciplinary attitude, but through real, two-way exchanges among the various stakeholders in the research outcomes. Others have recognized the importance of this lesson:

> There is probably no single important problem of society that can be understood exclusively from any single discipline (Wenk 1986, taken from Batie 1992:21).
>
> Rather than thinking of the public as of in need of education, the public should be admitted as full partners to the decision-making process. However, by calling for more scientific participation in public debate, I do not mean to imply that there is a need to "educate the public." Such a paternalistic "we are the experts, and our values count" approach is precisely what is being indicated. Instead of a one-way lecture from researchers to the public, there needs to be unbiased dialogue. It is important that such a dialogue focus on definition of goals and the design of desired outcomes (Batie 1992:25).

Failure to learn this lesson has been an important factor in unsuccessful public and private research. The time and effort spent on engaging in dialogue with the stakeholders in our project have led to their continuous, enthusiastic support. Without this support, the project could not have survived. We will carry this realization with us to future endeavors, along with the belief that, through research and education, commercial agriculture can achieve improvements in sustainability.

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Appendix A

Gregory A. Porter

GENERAL METHODS

Site Selection and Preparation

The study was established on the University of Maine's Aroostook Research Farm in Presque Isle, Maine. The site selected for the study consisted of a tract with approximately 35 tillable acres on the north side of the research farm. This land had a long history of commercial potato production and in 1985 was deeded to the University for research use. The site topography is irregular and separated into three fields. Two of the fields, consisting of 75% of the area, have a general 3% to 8% westward slope while the third field is relatively level with scattered bedrock outcrops. The entire tract is mapped as the Caribou loam soil type (fine-loamy, mixed, frigid, Typic Haplorthods) with occasional pockets of the Conant soil type. Caribou loam soils are gravelly and well drained with extensive coarse fragments. The Conant soil type is similar, but with slightly poorer drainage. Both soil types are widely used for potato production in the region.

The two larger, sloping fields of the research site had been used for commercial potato production during 1989, while the remaining field produced oats underseeded with red clover and timothy. Soil samples were collected during the spring of 1990 to document the general soil pH and fertility levels on the site. The fields cropped to potatoes during 1989 were planted to a millet cover crop. The remaining field was left in a red clover/timothy cover crop. Both cover crops were moldboard plowed during fall 1990. The research plots for the present study were laid out during spring of 1991. Care was taken to use only the most uniformly sloped portions of the site. The total land area in research plots consisted of 14.3 acres. The remaining land area in the original 36-acre tract was used for component research studies, alleys and roadways, or it was seeded to timothy and red clover hay if it was unsuitable for research use.

Based on soil samples collected during the spring of 1990, dolomitic limestone was spread and surface incorporated before planting the 1991 research plots. The goal of the liming program was to slowly equalize the pH levels across the fields and to eventually bring all fields to pH levels that would be desirable for all crops in the system. Initial pH levels were less than 5.0 on one field and repeated lime applications were needed to bring the pH to

Table A1. Initial soil conditions and subsequent lime applications.

Soil Characteristic/Lime Application		Soil Results by Initial Field Designation Field #1	 Field #2	 Field #3
Block(s) of Experiment		One	Two, Three	Four
Initial Soil Conditions[1]				
pH		5.25	5.15	4.60
Phosphorus	lbs/A	21.8 H	23.6 H	35.6 H
Potassium	"	385 VH	383 VH	360 VH
Magnesium	"	328 H	322 H	97 L
Calcium	"	1582 MH	1176 M	640 L
Cation Exchange Capacity (meq/100gm)		6.6	5.9	5.7
Potassium	% saturation	7.4	8.3	8.1
Magnesium	"	20.3	22.2	6.8
Calcium	"	59.6	49.2	27.2
Lime Applications (lbs/A)				
13–14 May 1991		None	2000	2400
22 October 1991		None	None	2050
10 May 1993		None	None	1900

[1] Soil samples were collected during May 1990.

General Soil Fertility Guides: L=low; M=medium; MH=medium-high; H=high; VH=Very high or excessive.

desirable levels. Appendix Table A1 provides a summary of the initial soil conditions on the research site and the lime applications conducted during the 1991–1994 seasons.

Experimental Design

The experiment consisted of 14.3 acres of research plots during each growing season (7.15 acres each of rotation crops and potatoes). Pest management systems were laid out as the mainplot factor in a split-plot, randomized complete block design experiment. This was done to help reduce the movement of insect pests and natural enemies among plots receiving varied pest management treatments. Subplots consisted of soil management systems (amended vs unamended), varieties (Atlantic vs Superior), and crop rotation entry points (potatoes vs rotation crop). Both rotation crop entry points were included in the experiment so that both entry points of the two-year crop rotations (potatoes vs rotation crop) were present in each growing season. The subplots were set up as a 2×2×2 factorial combination of soil management system, variety, and rotation entry point; therefore, within each mainplot, there were eight subplots (0.149 acres each, 48 ft wide × 135 ft long). With eight subplots, each pest management system mainplot was 1.192 acres in planted area. Rotation crop and potato plots were alternated in a "patchwork" pattern to help reduce the movement of insect pests and natural enemies among plots. There were four replications of each treatment combination in the experiment giving 12 total pest management mainplots and 96 total subplots. The replications were blocked so each treatment appeared once in each block. Each block consisted of an individual field or part of a field with a similar cropping history and relatively uniform soil conditions at the start of the experiment. Relatively large soil fertility differences existed among the blocks at the start of the experiment (Appendix Table A1).

Management Systems and Potato Varieties

Three pest management systems were compared during each year of this study. During 1991, the three pest management systems were conventional, reduced input, and no pest control. *From 1992 through 1994, the three pest management systems were conventional (CONV), reduced input (RI), and biological (BIO).* Briefly, CONV represents pest control mainly via application of commercially available chemicals that are typically recommended by the University of Maine Cooperative Extension. Pest management decisions are based on economic threshold values when such criteria are available for a particular pest. The RI pest management system makes use of the same chemicals as CONV, but attempts to reduce the amount of agricultural chemicals applied to the system. For example, application rates of herbicides are one-half those of the CONV system, and vine desiccants are applied only once at the standard rates rather than twice. Also, economic threshold values used in insect pest management are doubled. The BIO system uses only biological approaches, natural chemicals, or cultural practices for pest management. The materials used, timing of practices and applications, and management decision criteria for each system have evolved as the study has progressed (details of the specific insect, disease, and weed management systems are presented in Chapters 3, 4, and 5).

Two soil management systems, unamended and amended, and two potato varieties were compared in factorial combination within these pest management systems. *The two potato varieties grown in this experiment were Atlantic (disease and stress tolerant) and Superior (disease and stress susceptible).* Both varieties currently are widely grown in Maine and the eastern United States. The soil management systems have evolved considerably as the study has progressed. The philosophy of the soil management system treatments has been to compare a conventional, chemical-based system (unamended) to one which adds large quantities of organic amendments and residues to the soil (amended). The hypothesis being tested is that the organic amendments would improve the "quality" of the soil system and over time would improve the productivity of the soil. A summary of the specific practices used in the two soil management systems is presented in Appendix Tables A2 and A3.

The unamended soil management system generally consists of a two-year crop rotation with potatoes grown after a grain crop and with nutrient needs met with chemical fertilizer applied at recommended rates based on soil test data. The grain crop used in this soil management system was barley underseeded with medium red clover. Potatoes in the unamended soil management system have received 1000 to 1200 lbs/A of 10-10-10 fertilizer at planting and a supplemental application of nitrogen sidedressed at or before tuber initiation of each growing season. The major exception to this program was that at-planting chemical fertilizer was inadvertently omitted from the unamended plots of the BIO pest management system during 1992. An additional broadcast potash application was applied to the unamended soil management system during the spring of 1994 to correct a pattern of declining soil potassium levels.

The crop rotation used in the amended soil management system was initially a two-year rotation of potatoes grown after barley underseeded with medium red clover. As the experiment has developed, a green manure rotation crop has replaced barley as the rotation crop in this system. The transition to the green manure rotation crop is detailed in Appendix Table A3. All potato plots in the amended system followed a grain crop during 1992, while all followed a green manure crop during 1994. The transitional year was 1993, in which potatoes in the BIO pest management system followed green manure while those in the RI and CONV pest management systems followed barley. The green manure crop produced during 1992 consisted of peas, oats, hairy vetch, and berseem clover seeded as a mixture. During 1993 and 1994, the berseem clover was dropped from this mix since it contributed little biomass to the mixture.

Potato plots in the amended soil management system received an application of waste potato compost and cattle manure each spring before primary tillage. The compost was applied first and was followed by the manure when weather and soil conditions

Table A2. Description of nutrient management systems and dates of planting, vine destruction, and harvest.

Year	Pest Mgt. Sys.	Soil Mgt. System	Compost Rate	Manure Rate	Fert.[1] + Planting Date	Nitrogen Side-dress Rate	Vine Destruc. Date	Harvest Date
1991	All	Unamended	—	—	1000 lbs/A 5/30	54 lbs/A 7/15–16	9/11–12	9/24–10/5
		Amended	6 tons/A 5/16–21	20 tons/A 5/22	450 lbs/A 5/31–6/3	54 lbs/A 7/15–16	9/11–12	9/24–10/5
1992	CONV	Unamended	—	—	1000 lbs/A 5/26–27	53 lbs/A 7/16	9/8	9/22–28
		Amended	10 tons/A 5/13–15	20 tons/A 5/16	450 lbs/A 5/28	53 lbs/A 7/16	9/8	9/22–28
	RI	Unamended	—	—	1000 lbs/A 5/26–27	53 lbs/A 7/16	9/8	9/22–28
		Amended	10 tons/A 5/13-15	20 tons/A 5/16	450 lbs/A 5/28	53 lbs/A 7/16	9/8	9/22–28
	BIO	Unamended	—	—	— 5/29	59 lbs/A 7/17	9/8	9/22–28
		Amended	10 tons/A 5/13–15	30 tons/A 5/16	— 5/29	59 lbs/A 7/17	9/9	9/22–25
1993	All	Unamended	—	—	1200 lbs/A 5/26–27	45 lbs/A 7/8–9	9/8	9/21–24
		Amended	10 tons/A 5/12–17	20 tons/A 5/18–19	560 lbs/A 5/28	45 lbs/A 7/8–9	9/8	9/21–24
1994	All	Unamended	—	—	1200 lbs/A[2] 5/27–31	53 lbs/A 6/28–30	9/9	9/23–27
		Amended	10 tons/A 5/17–19	20 tons/A 5/19–20	600 lbs/A 5/31–6/3	—	9/9	9/23–27

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[1] Complete fertilizer rate applied at planting. Fertilizer analysis was 10% each N, P_2O_5, and K_20.

[2] In addition to at-planting fertilizer application, 80 lbs/A of K_2O (as KCl) was broadcast onto blocks 1–3 of the unamended soil management system before spring tillage. A similar application of 160 lbs/A of potash was applied to block 4. These applications were scheduled to maintain optimum soil potassium levels.

Table A3. Crop rotation sequence by management system.

Pest Mgt. System	Soil Mgt. System	Entry Point	Crop by Growing Season 1991	1992	1993	1994
CONV	Unamended	1	Potato	Barley	Potato	Barley
		2	Barley	Potato	Barley	Potato
	Amended	1	Potato	Barley	Potato	Green Manure
		2	Barley	Potato	Green Manure	Potato
RI	Unamended	1	Potato	Barley	Potato	Barley
		2	Barley	Potato	Barley	Potato
	Amended	1	Potato	Barley	Potato	Green Manure
		2	Barley	Potato	Green Manure	Potato
BIO	Unamended	1	Potato	Green Manure	Potato	Barley
		2	Barley	Potato	Barley	Potato
	Amended	1	Potato	Green Manure	Potato	Green Manure
		2	Barley	Potato	Green Manure	Potato

Note: All barley crops were underseeded with berseem clover. Green manure consisted of a mixture of oats, peas, vetch, and berseem clover during 1992 and oats, peas and vetch during subsequent growing seasons.

allowed. Both amendments were spread on the soil surface with a manure spreader and then disked into the soil surface as soon after manure application as was possible. The waste potato compost was produced by a local potato producer (H. Smith Packing, Westfield, ME). Nutrient content of both amendments was determined from samples randomly collected in the spring before spreading. Although rates of amendment application varied slightly among years (see Appendix Table A2), compost was applied at 10 tons per acre (f.w. basis) and manure was applied at a rate of 20 tons per acre (f.w. basis). From 1991 to 1993, compost was applied before both potatoes and the rotation crop in this system, while manure was applied only before potato production because the potato crop was expected to receive the most benefit from the nutrients within the manure. Compost application to the rotation crops was discontinued during 1994. Based on nutrient analysis of the organic amendments and anticipated availability (Appendix Table A4), we attempted to develop a nutrient management strategy that would exploit the nutrients in the amendments and use a reduced rate of chemical fertilizer. The goal was to approximate the fertility levels available in the unamended system. At-planting chemical fertilizer rates were reduced to 450 to 600 lbs/A of 10-10-10 in this system depending on the growing season (Appendix Table A2). During 1992, however, we attempted to produce the potato crop without at-planting chemical fertilizer in the amended system of the BIO pest management system. Although we increased the manure application rates in this system during 1992, crop growth was inadequate. Therefore, we returned to the strategy described above for the 1993 and 1994 growing seasons. As was described for the unamended soil management system, an additional nitrogen application was sidedressed at or before tuber initiation in the amended soil management system during 1991 through 1993. Based on tissue

Table A4. Compost and manure analysis by growing season.

Organic Amendment Characteristic		Analytical Results by Growing Season 1991	1992	1993	1994
Waste Potato Compost (d.w. basis):					
pH		7.6	7.46	8.72	8.0
Water	%	57.9	86.2	59.0	71.1
Total Nitrogen	%	0.51	0.56	0.76	1.49
Ammonium Nitrogen	%	0.11	0.04	0.05	0.08
Potassium	mg/kg	1967	4292	6335	11500
Phosphorus	"	1970	3601	1585	5370
Calcium	"	7620	4534	7655	9330
Magnesium	"	4307	—	3780	4380
Cadmium	"	0.6	—	1.2	1.3
Copper	"	22	—	20.5	30
Zinc	"	79	—	119.5	122
Boron	"	—	—	42	44
Beef/Dairy Manure (f.w. basis):					
pH		—	—	8.48	8.3
Water	%	42.2	65.3	68.0	71.0
Total Nitrogen	%	0.46	0.70	0.45	0.53
Ammonium Nitrogen	%	0.09	0.13	0.12	0.19
Potassium	mg/kg	1500	2733	2885	1550
Phosphorus	"	2367	2633	1385	1430
Calcium	"	—	—	5230	2590
Magnesium	"	—	—	2010	1220
Cadmium	"	—	—	—	—
Copper	"	—	—	6.8	6.2
Zinc	"	—	—	35.2	23.2
Boron	"	—	—	12	5.6

testing of the potato crop, we determined that sidedressed nitrogen was not necessary during 1994.

Cultural Practices

Potatoes

Before potato planting in the spring, the plots entering the potato phase of the rotation were disked twice to break up the soil and to incorporate amendments and crop residues. The plots were then lightly harrowed to smooth the soil surface. During 1994 the plots were disked only once. Potatoes were then planted with a conventional, "pick-type," two-row potato planter. Rows were spaced 36 in. apart with an average seedpiece spacing of 9.3 in. within the row. Average planting depths were typically 2 to 4 in. below the soil surface after dragging off the planter row. Certified or better potato seed was used during all growing seasons. In most years, we attempted to plant whole, B-sized potato seedpieces; however, we had to accept cut seed when supplies of the smaller-sized seed were limited. For example, cut seed of Atlantic was used for the 1994 growing season and many seedpieces of Atlantic had to be split during 1991.

The at-planting fertilization program consisted of commercially available 10-10-10 blended chemical fertilizer. This material was applied by the conventional potato planter in bands located two inches below and to each side of the potato seedpieces. Application rates and timings are presented in Appendix Table A2. Supplemental nitrogen fertilizer was applied at or before tuber initiation during each year. This supplemental nitrogen fertilizer application consisted of liquid UAN (32% nitrogen by weight) solution sprayed onto the soil surface as the potatoes were hilled. Rates and times of application are summarized in Appendix Table A2.

The weed management program consisted of a combination of cultural and chemical methods depending upon the pest management system. Details are provided in Chapter 3. Insect and disease management strategies varied depending upon the year and the pest management system. Details are provided in Chapters 4 and 5. Spray application of chemical and biological materials was achieved with a conventional farm sprayer equipped with an 8-row (24-ft) spray boom so that it could be easily used in research plots.

Vine destruction was scheduled for approximately 105 days after planting. This duration of growth generally provides adequate maturity and yields for these two potato varieties under northern Maine conditions. After the 1991 growing season, all plots in the CONV and RI pest management systems were rolled before vine desiccation. Vine destruction methods varied with pest management system in this study. Vine desiccation in the CONV system was achieved with two applications of diquat plus a surfactant (1 pt/A of diquat plus 1 pt/A surfactant). The second application was applied five to seven days after the initial desiccation treatment. The RI system made use of the same materials and initial rates, but relied on a single application. The BIO system was treated the same as the RI system during 1991. During subsequent growing seasons, however, we relied exclusively upon mechanical destruction of the vine with a flail mower. Dates of the initial vine destruction treatments for each year are presented in Appendix Table A2.

Potato plots were left untilled after harvest in 1991. From 1992 through 1994, the harvested potato plots were fall chisel plowed across the prevailing slope of the land. Tillage depth was approximately 10 in.

Barley

After seedbed preparation in the spring, the barley (cv. 'Robust') plots were seeded at approximately 120 lbs/A with a conventional, 10-ft grain drill. Row spacing was 7 in. During 1991, the seedbed was prepared by disking each plot twice and then smoothing the plots with a harrow. Seedbed preparation during 1992 and 1993 was conducted with two passes using a deep harrow. Only one tillage pass was used during 1994. Red clover, inoculated with rhizobia, was seeded simultaneously at 10 lbs/A. In all management systems, ammonium nitrate was applied at seeding to supply sufficient nitrogen for vigorous growth. When weather conditions allowed an additional nitrogen topdress was broadcast onto the barley plots after tillering. Details of barley production practices are provided in Appendix Table A5. Aside from the nitrogen applications and weed control program, no chemical applications occurred in the barley plots after planting. Two 59-in.-wide swaths (0.0152 acres each) were harvested from each plot with a small-plot combine to determine grain yield. After the grain yield and biomass samples were removed (see Chapter 2 for sampling method), the plots were combined to remove the remaining grain and to spread the remaining straw on the soil surface. Barley plots were left untilled through the 1991 and 1992 fall seasons, but were chisel plowed across the prevailing slope during fall 1993 and 1994.

Table A5. Cultural practices for the barley and green manure rotation plots (excluding pest management).

		Seeding Rates and N-fertilizer (lbs/A)				Dates of Sampling and Cultural Practices			
Growing Season		Barley	Nitrogen At-Planting	Clover	Nitrogen Topdress	Nitrogen Topdress	Quadrate Sampling	Grain Harvest	Fall Tillage
Barley Rotation Plots									
1991	May 22–31	120	40	10 Medium	11	July 11	Aug. 23–28	Sept. 6	None
1992	June 3	120	34	10 Mammoth	None	—	Sept. 3–10	Sept. 10–15	None
1993	May 24	120	34	10 Mammoth	42	June 28	Aug. 26–27	Sept. 8	Chisel Plow October 26
1994	May 25	120	34 Medium	10	40	June 24	Aug. 18–24	Aug. 26	Chisel Plow October 19–20
		Seeding Rates of Green Manure Components (lbs/A)							
Green Manure Plots		Oats	Peas	Vetch	Clover				
1992	June 4–5	32	117	25	10		Sept. 10–16	—	Moldboard Plow October 13–14
1993	June 16	48	150	30	—		Oct. 5–6	—	Chisel Plow October 26
1994	June 6	48	150	30	—		Oct. 7–12	—	Disk and Chisel Plow October 19–21

Green Manure

The green manure crop produced during 1992 consisted of 'Columbia' peas, 'Porter' oats, hairy vetch, and berseem clover seeded as a mixture. During 1993 and 1994, the berseem clover was eliminated because it contributed little biomass to the mixture. The oat seeding rate increased and the pea cultivar 'Trapper' was used instead of 'Columbia'. Seeding dates, cultural practices, and fall tillage dates for the green manure rotation crops are listed in Appendix Table A5. Seedbed preparation was the same as that listed above for the barley crop. Seeding during 1992 was achieved with three passes using conventional 10-ft wide grain drill and 7-in. row spacing. The oats and inoculated clover were seeded in the first pass through the plots. The inoculated peas and hairy vetch were seeded in the second and third passes, respectively. The seeder was modified with an additional seedbox before the 1993 growing season. With the oats and peas mixed together, this additional seedbox allowed seeding of the oats, peas, and vetch in a single pass through the plots. No fertilizers or herbicides were applied to the green manure crop.

Soil Amendment Loading Rates—Compost and Manure

Loading rate limits for manure and compost were calculated using methods from Reed et al. (1988) and Huddleston and Ronayne (1990). Annual limits based on nutrients (nitrogen and phosphorus) and cumulative limits based on metals (cadmium, copper and zinc) were determined. The loading rates are based on crop requirements (annual) and maximum allowable metal concentrations in soil (cumulative), taking into account potential risks to ecosystems. Allowable loading rates for compost and manure, based on crop uptake and metal accumulation, are presented in Appendix Tables A6 and A7. Exact methods and example calculations are contained in the following section.

ALLOWABLE COMPOST AND MANURE LOADING RATES

The results of loading rate computations are presented in Appendix Tables A6 and A7. They are relatively restrictive (conservative) rates. Actual loading rates were well below these values, except phosphorus. Special care should be exercised to ensure that there is not a build up of phosphorus in these plots. Example calculations are included below. These are representative illustrations, which indicate whether selected loading rates are excessive based on agronomic (i.e., annual loading rates) or environmental

Table A6. Allowable soil amendment loading rates—Crop uptake basis (tons/A).

Nutrient - Amendment	1991	1992	1993	1994
Dry Solids Basis				
N - Compost	355	470	350	190
P - Compost	9	5	11	3.5
N - Manure	125	50	70	50
P - Manure	4.5	2	4	3.5
Fresh Weight Basis				
N - Compost	845	3420	860	655
P - Compost	21	35	26	11
N - Manure	215	150	215	170
P - Manure	7.5	6.5	12.5	12.5
Actual Loading Rates (fresh weight)				
Compost	6	10	10	10
Manure	6	20	20	20

Assumes annual crop uptake of 205 lb/A/year of N and 18 lb/A/year of P. For ease of computation, residual organic N is not considered.

Table A7. Allowable soil amendment loading rates—Metal accumulation basis (tons/A).

Nutrient - Amendment	1991	1992	1993	1994
Dry Solids Basis				
Compost				
Cadmium	7420	—	3710	3420
Copper	11325	—	6080	2075
Zinc	3155	—	2085	2040
Manure				
Copper	—	—	5865	5830
Zinc	—	—	2265	3115

Assumes maximum cumulative loading rates of 9 lbs/A for cadmium, 250 lbs/A for copper, and 500 lbs/A of zinc.

(i.e., cumulative loading rates) considerations. The examples provided below use duplicate samples collected from the 1991 compost piles just before spreading. An equivalent approach could be used for the amendments applied during 1992 to 1994.

Metal Accumulation Analyses

Assuming a sandy loam to loamy soil with CEC between 5 and 15 meq per 100 g, the allowable cumulative loadings of metals on agricultural lands are as follows:

cadmium: 9 lb/A   copper: 250 lb/A   zinc: 500 lb/A

Cumulative loading rates of the compost based on amendment analyses are:

R_m = 0.0005 * Allowable Loading (lb/A)/Compost Metal Concentration (decimal fraction)

Cadmium
Sample 1: R_m = 0.0005 (9)/(4.7E-7) = 9575 t/A
Sample 2: R_m = 0.0005 (9)/(5.5E-7) = 8180 t/A

Copper
Sample 1: R_m = 0.0005 (250)/(1.63E-5) = 7670 t/A
Sample 2: R_m = 0.0005 (250)/(2.2E-5) = 5680 t/A

Zinc
Sample 1: R_m = 0.0005 (500)/(6.77E-5) = 3695 t/A
Sample 2: R_m = 0.0005 (500)/(7.87E-5) = 3175 t/A

Nutrient Loading Analyses

Nitrogen loading

Available nitrogen is determined by:

N_a = 602 (Nitrate + Ammonium * Volatilization Factor + Organic Nitrogen * Mineralization Factor),

where the nitrogen species are expressed as decimal fractions. Organic nitrogen mineralization rates for compost, e.g., are 10% for Year 1, 5% for Year 2, and 3% for Year 3 and every year after that. Compost that is surface applied and immediately incorporated suffers essentially no volatilization losses, thus making the volatilization factor equal to 1; unincorporated material has a volatilization factor of 0.5.

Assume that Sample 1 contains 0.1 % ammonium and 0.31 % organic nitrogen, and that Sample 2 contains 0.11 % ammonium and 0.4 % organic N. For Year 1, Sample 1 would yield:

$$\begin{aligned} N_a &= 602\,(0 + (0.001 * 1) + (0.0031 * 0.1)) \\ &= 0.79 \text{ lb N/ton dry solids} \end{aligned}$$

Similarly for Sample 2:

$$\begin{aligned} N_a &= 602\,(0 + (0.0011 * 1) + (0.0040 * 0.1)) \\ &= 0.9 \text{ lb N/ton dry solids} \end{aligned}$$

Assuming a crop uptake of 205 lb N/A/year, approximately 260 and 225 dry tons of compost could be applied annually.

Phosphorus loading

Phosphorus loading calculations are similar to those for metal loading.

$$R_p = K_p\, U_p \,/\, C_p$$

If the constant is equal to 0.001, assumed crop uptake is 18 lb/acre/year, phosphorus concentrations in Samples 1 and 2 are 1460 ppm and 1970 ppm, respectively, then

Sample 1: $R_p = (0.001)\,(18)\,/\,(0.00146)$
$= 12.3$ dry tons/acre/year

Sample 2: $R_p = (0.001)\,(18)\,/\,(0.00197)$
$= 9.1$ dry tons/acre/year

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Appendix B

Francis A. Drummond

SAMPLING THE COLORADO POTATO BEETLE

In the late winter of 1991, we designed a sampling plan for the Colorado potato beetle (CPB). We based our optimal sample size estimates upon research conducted by Logan (1981). He estimated sample size from three years of sampling CPB egg masses and larvae on Superior potatoes grown in Rhode Island. We selected a sample size of 30 plants per plot which based upon his data should result in precisions (standard error: mean ratios) of 0.1 to 0.5 over a range of egg mass (0.1–2.0/plant) and larval (0.1–8.0/plant) densities. After four years of sampling potato beetle we now can evaluate and improve our sampling scheme. An optimal sampling plan has to be designed with specific objectives in mind. For instance, if the only reason for a census is to determine whether the economic threshold has been reached, then a sequential sampling plan might be designed to optimize sampling time relative to the uncertainty of assessing whether the threshold has been reached. Unfortunately, a sequential sampling plan designed around economic thresholds would be of little use in compiling a chronological history of the population dynamics of the CPB. For this objective, a fixed sample size based upon density/plant or binomial sampling (presence or absence sampling) might be more appropriate. Our research project is concerned with describing the ecological interactions of multiple pests in potato plots in response to experimental treatments, and with estimating insect density to compare with economic threshold levels for timely management decisions. Therefore, we are forced to develop a sampling plan that incorporates the largest allowable precision for a range of pest species density estimates.

A random sampling plan for each plot is essential for our needs although management decisions are made on a block basis. This is because our statistical analyses require estimates of plot-level dynamics. In addition, we feel that sampling must not destroy the plant because the plots are not large enough to allow hundreds of plants to be excavated. Many sampling plans for the CPB (Dwyer et al. 1994) are based upon a changing sample unit, the potato stem. This is not suitable for our needs because as stem density changes, insects per stem will increase or decrease without a change in insect abundance in the field. Therefore, the whole plant is the lowest level sampling unit that is stable throughout the growing season and meets our needs.

The relationship between the mean and variance is the major factor determining the number of samples necessary for estimating a field density of insects with a desired precision level. To estimate the mean and variance, Taylor regressions (i.e., relationships between the logarithm of the mean density and the logarithm of the variance of the density [Taylor 1961]) were performed on the insect count data collected between 1991 and 1994. Table B1 shows the coefficient estimates for the Taylor regressions of CPB egg masses, small larvae, large larvae, and adults for 1991–1994 (Taylor 1961). The spatial pattern for the life stages of the CPB is fairly consistent except for higher slope values in 1993. A pooled regression (1991–1994) was fit to all the data in order to develop a single description of spatial distribution for each life stage. The Taylor regressions can be interpreted by analyzing the slope. If the slope is equal to one then the population can be considered randomly distributed in a

Table B1. Coefficients of Taylor regressions[1] representing the spatial dispersion of Colorado potato beetle stages in the field, 1991–1994.

CPB Life Stage	Year	Intercept ± 95% CI	Slope ± 95% CI	r^2	n
Adults	1991	0.013 ± 0.0004	1.21 ± 0.0032	0.94	768
	1992	-0.122 ± 0.0002	1.11 ± 0.0011	0.98	576
	1993	0.014 ± 0.0001	1.65 ± 0.0026	0.94	528
	1994	0.011 ± 0.0005	1.14 ± 0.0010	0.87	480
	1991–1994	0.012 ± 0.0002	1.18 ± 0.0020	0.91	2352
Egg Masses	1991	-0.001 ± 0.0011	1.01 ± 0.0014	0.86	768
	1992	-0.060 ± 0.0023	1.07 ± 0.0030	0.85	576
	1993	0.001 ± 0.0001	1.52 ± 0.0029	0.94	528
	1994	-0.001 ± 0.0001	1.14 ± 0.0016	0.89	480
	1991–1994	0.017 ± 0.0004	1.28 ± 0.0021	0.88	2352
Small Larvae	1991	0.001 ± 0.0001	1.61 ± 0.0033	0.92	768
	1992	-0.213 ± 0.0001	1.62 ± 0.0040	0.90	576
	1993	0.101 ± 0.0008	2.22 ± 0.0051	0.87	528
	1994	0.066 ± 0.0001	1.84 ± 0.0010	0.94	480
	1991–1994	0.032 ± 0.0003	1.91 ± 0.0003	0.91	2352
Large Larvae	1991	0.024 ± 0.0003	1.44 ± 0.0002	0.94	768
	1992	0.017 ± 0.0006	1.41 ± 0.0030	0.88	576
	1993	0.020 ± 0.0001	1.35 ± 0.0020	0.84	528
	1994	0.001 ± 0.0001	1.44 ± 0.0011	0.87	480
	1991–1994	0.009 ± 0.0001	1.38 ± 0.0002	0.88	2352

[1] The regressions are of the form: log (S2) = intercept + slope*log (mean).

field. A slope less than one suggests a uniform distribution, and an aggregated slope suggests a highly aggregated or clumped population. The spatial pattern of CPB life stages is most aggregated for the small larvae followed by the large larvae, the egg masses, and then the adults. This can be explained biologically. Small larvae exist in a clumped distribution upon hatching from the egg mass, while large larvae and adults have increasingly greater mobility and move about, which results in a less aggregated distribution. These relationships were used to estimate a variance for a given mean density and substituted into the following formula (Elliot 1977) for estimating fixed optimal sample sizes for various mean densities:

$$n = (S^2)/(D^2 * m^2)$$

where:

n = optimal sample size to be calculated (number of potato plants to be sampled,

S^2 = the estimated variance derived from the Taylor regression for a given mean density of CPB (back transformed),

D = a measure of precision (standard error to mean ratio) close to 0 (very high) and infinity (low),

m = the mean density thought to exist in the field at the time of sampling.

Table B2 summarizes the fixed optimal sample sizes given a range of precisions and CPB population densities for egg masses, small larvae, large larvae, and adults. Based upon the data collected between 1991 and 1994 and a sample size of 30 plants per plot, our estimates of density relative to economic thresholds had precisions that ranged between 15% and 19%. Levels of precision equal to or less than 25% are considered adequate for pest management decision making (Southwood 1978). If pest management decisions were made at a plot level, 95% confidence intervals would range from 29.4% to 37%, or, as an example, for a large larval threshold of 1.5 larvae/plant, an estimate falling between a true density of 1.275 and 1.73 larvae/plant would be considered at the threshold. However, our pest management decisions were made at the block level (four plots in each pest management strategy per block). This means that the economic threshold was estimated from 120 plants (ignoring the strata of the plot). The levels of precision for 120 plants were of course much higher. Table B2 suggests that precision levels at the block level ranged from 6% to 12%, well under the target level of precision of 25%. Therefore, our sample

Table B2. Optimal sample size[1] (number of potato plants that should be sampled per field) for a random sampling plan with a fixed level of precision.

		# Samples Needed for Precision of		
CPB Life Stage	Mean Density[2]	10%	20%	30%
Adults	0.1	679	169	75
	0.5	**181**	**45**	**20**
	1.0	103	26	11
	2.0	58	15	6
	4.0	33	8	4
	8.0	19	5	2
Egg Masses	0.1	546	136	61
	0.5	171	43	19
	1.0	104	26	12
	2.0	63	16	7
	4.0	38	10	4
	8.0	23	6	3
Small Larvae	0.1	181	45	20
	0.5	157	39	17
	1.0	148	37	16
	2.0	139	35	15
	4.0	**130**	**33**	14
	8.0	122	31	13
Large Larvae	0.1	425	106	47
	0.5	157	39	17
	1.0	102	26	11
	1.5	**79**	**20**	**9**
	2.0	66	17	7
	4.0	43	11	5
	8.0	28	7	3

[1] If one desires a 0.95 level of probability that the optimal sample size will yield the desired precision then each sample size must be multiplied by z^2 (the square of the standard normal variate) or approximately 3.84.

[2] The **bold** means and respective sample sizes are for the economic threshold levels of the CONV pest management system.

size of 30 plants per plot yielded precise estimates of CPB density (except at very low densities, less than 0.5 CPB life stages/plant) at both the plot level (for population dynamics studies) and at the block level (for pest management decision making). If one wanted to optimize the sampling block estimate, then a two-stage strategy would suggest that plot samples should be maximized relative to plants within a plot. This is essentially the procedure that we have adopted since we sample all plots within a block.

Another approach to developing a sampling plan for the CPB is called sequential sampling. The general idea is that instead of taking a fixed number of samples, one samples until enough information is gathered so a decision such as an economic threshold can be made (Wald 1947) or a density estimate is achieved at a fixed level of precision (Green 1970). The sequential sampling strategy with a fixed level of precision is more suited to sampling populations for the study of insect ecology. This type of sampling has been used for sampling the CPB on tomato (Zehnder and Linduska 1988). In both cases as sampling is being conducted, a cumulative number of the insects to the number of plants sampled are compared. When a critical stopline (based upon this ratio and the spatial distribution of the insects) is reached, the sampling is stopped, and the density estimate or the control need is evaluated. The results of the Taylor regressions (Table B1) can be used to develop the critical stoplines (number of plants that should be sampled) according to the following formula (Green 1970):

$$\log (C) = (\log (D^2)/a)/(b - 2) + ((b - 1)/(b - 2) * (\log (n)))$$

where:

log = logarithm base 10

C = the cumulative number of insects sampled during the sampling of the plot,

D = a measure of precision (standard error to mean ratio) close to 0 (very high) and infinity (low),

a = the intercept of the Taylor regression,

b = the slope of the Taylor regression,

n = the number of potato plants sampled.

Using the Taylor regressions and substituting into Green's formula, stoplines can be estimated. These stoplines, estimated for precisions of 0.2 and 0.3, are shown in Figure B1. Close inspection of Table B2 reveals that the two sampling methods yield the same results, and that it is the way one samples, sequentially or with a fixed sample size, that determines the amount of labor. To execute the sampling plan, samples would be taken sequentially until the number of cumulative CPB exceeds the stopline for the number of cumulative potato plants sampled. At this time, the density of CPB can be calculated by dividing the cumulative number of CPB by the cumulative number of potato plants sampled. It is usually wise to make an adjustment to the stopline at extremely low densities, an upper limit can be set (Figure B1). One does not want to maintain a fixed level of precision if it means that 1200 potato plants have to

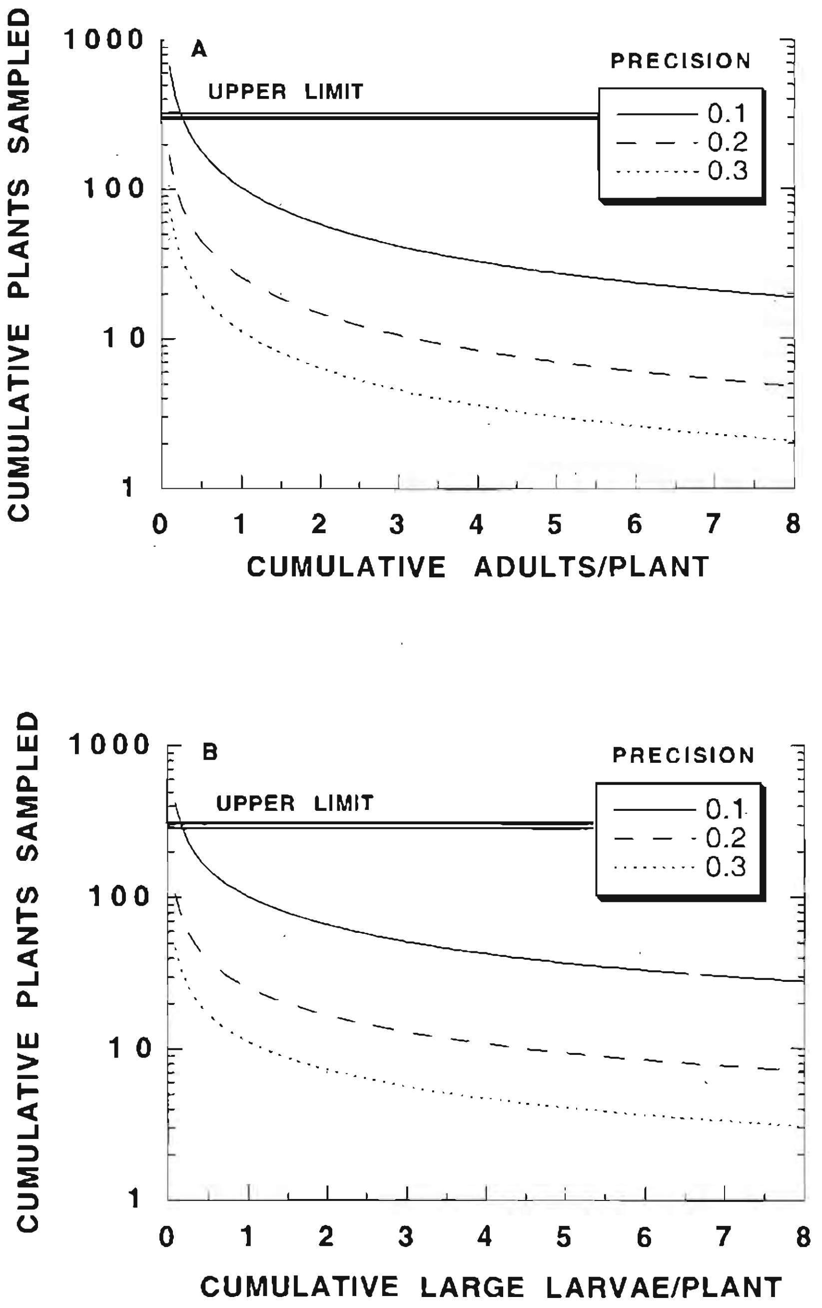


Figure B1. Variable sampling intensity plans for three levels of precision for adult CPB (a) and large larvae (b).

be sampled to estimate a density of 0.01 CPB/plant. This type of sequential sampling can reduce the sampling intensity when CPB densities are very high since the number of samples necessary for a given density will be less than the fixed optimal sample size.

Sequential sampling plans are more commonly derived for estimating whether the density of a pest is above or below an economic threshold (Binns 1993). This type of sampling is designed purely for pest management decision making (i.e., to spray or not to spray...that is the question). The description of the spatial distribution for the CPB can be used to develop a sequential sampling plan for a fixed level of precision and a fixed economic threshold (Martel et al. 1986). As an example we have developed a sequential sampling plan for CPB small larvae. Essentially, a sequential sampling plan for a single-threshold decision consists of two stoplines; one stopline is the lower limit, the other, the upper limit. If the number of cumulative insects sampled for a specific number of cumulative potato plants sampled exceeds the upper threshold, then the probability that the threshold has been reached is high, and a control decision needs to be made. If the cumulative number of insects is below the lower stopline, then sampling is stopped and the decision not to control the pest is accepted. If the cumulative number of insects is between the two stoplines, however, then no decision can be made with respect to the insect density relative to the economic threshold, and sampling more plants is necessary. Theoretically, sampling could continue forever if the population is truly in the "gray area" between the two stoplines. To prevent this, most pest managers implement a maximum number of plants that should be sampled for making any decision (Binns 1993). The maximum number of plants can be based upon a fixed optimal sampling plan (discussed previously). The equations for the stoplines (intercept and slope values assuming the normal distribution) that we constructed for CPB small larvae are as follows:

lower intercept = $(s^2/(m_0 - m_1)) * \ln(\beta/(1 - \alpha))$
upper intercept = $(s^2/(m_0 - m_1)) * \ln(1 - \beta/(\alpha))$
slope = $(m_1 + m_0)/2$

where:

s^2 = estimated variance when the population is at the threshold of 4.0 larvae per plant, this estimate is derived from the Taylor regression equation in Table 3,
m_0 = the mean density that can be considered below threshold, ca. 3.5,

m_1 = the mean density that is considered above the threshold, ca. 4.5, the distance between M_0 and M_1 is the "gray area" where one is not confident if the threshold has been reached,

α = 0.1 (based upon risk user is willing to take), the probability that the pest manager wants to use to guard against making a mistake by rejecting a pest classification when it is true (not spraying when the true insect population is really above the threshold),

β = 0.05 (based upon risk user is willing to take), the probability that the pest manager wants to use to guard against making a mistake by accepting a pest classification when it is false (spraying when the population is really below threshold),

ln = natural logarithm.

Figure B2 shows stoplines calculated for CPB small larvae, based upon our sampling data between 1991 and 1994. To implement this sampling scheme, one would sample a set of potato plants, for example 20. The number of small larvae observed on the 20 plants would be summed. If this sum is higher than the upper stopline, then sampling would be terminated and the decision would be made that the density of small larvae in the field was at or above threshold and control would be considered. If the sum is below the lower stopline, sampling would also be stopped and the decision not to spray would be accepted (CPB small larvae would be below threshold levels). If the sum is between the two stoplines, no decision would be made and another set of 20 potato plants would be sampled. The sum of 40 plants would be evaluated relative to the stopline directly above the 40-plant mark. The stoplines for cumulative CPB small larvae are 27 (lower) and 103 (upper) for a cumulative plant sample of 20 plants. This translates into mean CPB small larval densities of 1.4 larvae/plant and 5.2 larvae/plant. For 40 plants the stopline points are 2.4 larvae/plant and 4.3 larvae/plant, and for 50 plants the stopline points are 2.6 larvae/plant and 4.2 larvae/plant. Sequential sampling should save sampling time if pest densities in a particular field are extremely low or extremely high because one could detect densities well below or well above the threshold before sampling many plants. In contrast, a fixed sample size plan requires pest management scouts to sample the same number of plants (e.g., 100/field) irrespective of the pest densities. This section provides the parameters for characterizing the spatial distribution of the CPB. This information can be used by the reader for development of any number of CPB sequential sampling programs.

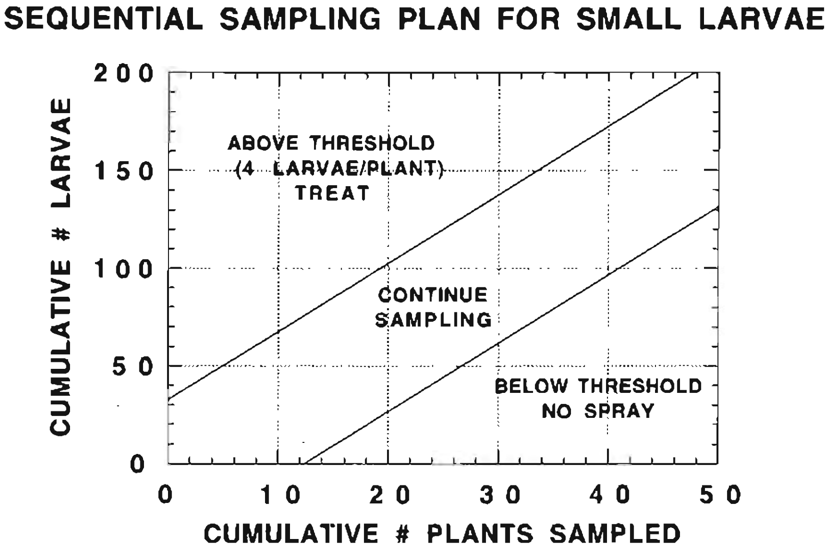


Figure B2. Sequential sampling plan for small larvea at a threshold of four small larvae per plant (Dwyer et al 1994).

SAMPLING APHIDS

A plan for sampling aphids can be developed similarly to the plan developed for the CPB. Aphids are also distributed in a clumped or aggregated manner (Taylor regression for total aphids in potato, 1991–1994 is $\log(s^2 + 1) = 0.465 + 1.962 * \log(\text{mean density} + 1)$, $r^2 = 0.94$). Aphids, however, are much more time consuming to count in the field. If the proportion of infested plants or leaves in a field are related to the density of aphids, however, then a sampling plan can be developed to estimate the presence or absence of aphids instead of the actual aphid density. Aphid density is then calculated from the proportion of infested leaves. This type of sampling plan has been called presence/absence sampling or binomial sampling. It can greatly reduce sampling costs for a given level of precision for hard to sample insects such as aphids, thrips, and mites (Southwood 1978).

We chose to use total aphid densities in barley and potato as examples in developing a few different types of presence/absence sampling plans. The first sampling plan is useful for estimating a proportion of plant infestation due to aphids when the grower or pest manager is not interested in the aphid density. For instance, in Maine the recommended economic threshold for aphids (not including winged green peach aphids) on table stock potatoes is 10% aphid infestation (Dwyer et al. 1994). Here the number of aphids per potato plant is clearly of no interest, only the proportion of plants that have at least one aphid. The optimal fixed sample size for a given level of precision is based upon the theoretical probability distribution of the positive binomial (Karandinos 1976). Figure B3 illustrates the dependent relationship between precision and sample size on the true proportion of infested plants (the object of estimation). It is clear that for a given level of precision (measured as a 95% confidence interval) more samples are necessary for estimates of infestation levels near 50% than levels approaching 0% or 100%. An estimate of 10% infestation with a 95% confidence level of 5% infestation (se/mean ratio ca. 25%) requires 110 samples, while a confidence level of 10% infestation (SE/mean ratio ca. 50%) requires a sample size of only 38 samples. The formula for calculating the necessary sample size for a given proportion and level of precision is given by Zar (1974) as:

$$n = D^2(p-1)$$

where:

n = number of samples necessary for optimal sampling
D = precision, in this case the variance of the proportion is $(p*q)/n$ and $c = (\text{variance})/p$
p = proportion of infested plants ($q = 1-p$)

A sequential sampling plan for a threshold of 10% infested potato plants can also be developed, similar to the sequential sampling plan for the CPB. The formula for calculating the stopline is given by Kuno (1969) and is

$$T_n = (n/2)\,(1 \pm \;(1 - 4D^2n))$$

where:

T_n = total number of sampling units infested in a sample size of n
n = number of plants sampled
D = desired level of precision

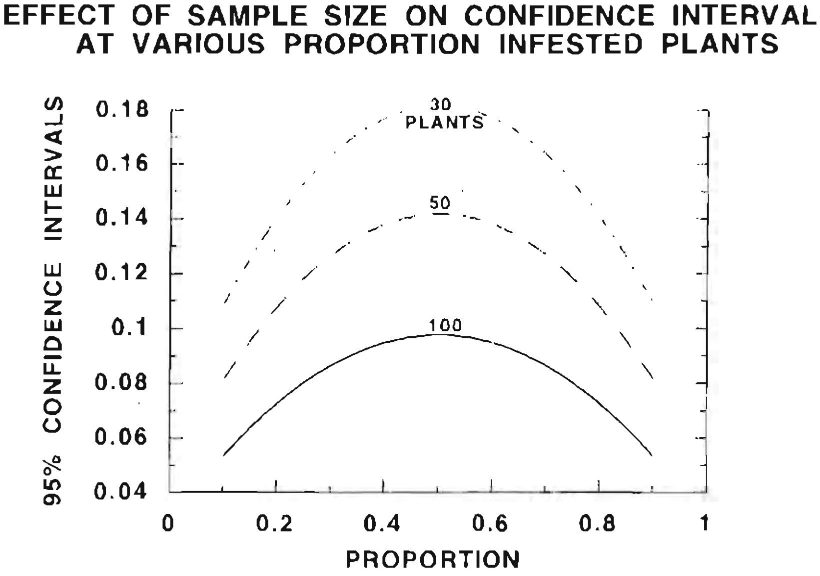


Figure B3. Relationship between the true proportion of infested plants in a potato field and the confidence (in terms of probability) about the sampled estimate for three sample sizes.

It should be noted that these sampling plans developed for estimating percentage infestation are not based upon the spatial distribution of the aphid, but rather on the theoretical distribution representing a binomial, or presence-absence, sampling. Thus, they can be developed in the absence of biological information specific to aphids in potato fields. Figure B4 shows the stoplines as functions of the number of plants examined for a threshold of 10% infestation and precisions of 0.10 and 0.20. The sampling would be carried out by sampling more plants until the stopline is exceeded (threshold has been reached) or until a specified number of plants has been sampled, such as 100. If the specified number of plants is reached before the stopline is exceeded, then the decision would be made that the threshold has not been reached and thus a control

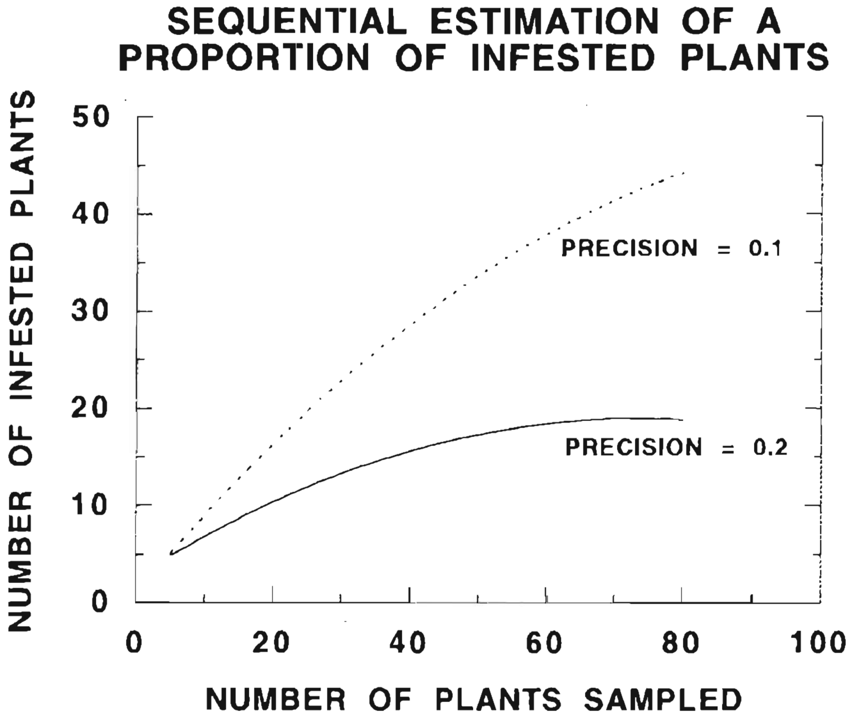


Figure B4. Sequential sampling plan at two levels of precision for estimating the proportion of infested plants in a potato field.

decision is not necessary. But, in this case it would be wise to conduct a follow-up sample soon, possibly the next day, to determine if this proportion, which is close to the threshold, will exceed it. Evidently as the need for higher precision arises, the number of samples for a given proportion will increase (Figure B4). Figure B5 illustrates that as the threshold (in terms of percentage of infested plants) increases the sample size decreases. Therefore, it will be less intensive to estimate 30% infestation (ca. 70 plants) then 10% infestation (ca. 110 plants) for a given level of precision (0.2). An alternate sequential sampling plan can be developed using a modification of the formula used to develop the sequential sampling plan for the CPB. The formula presented by Jones (1994) is

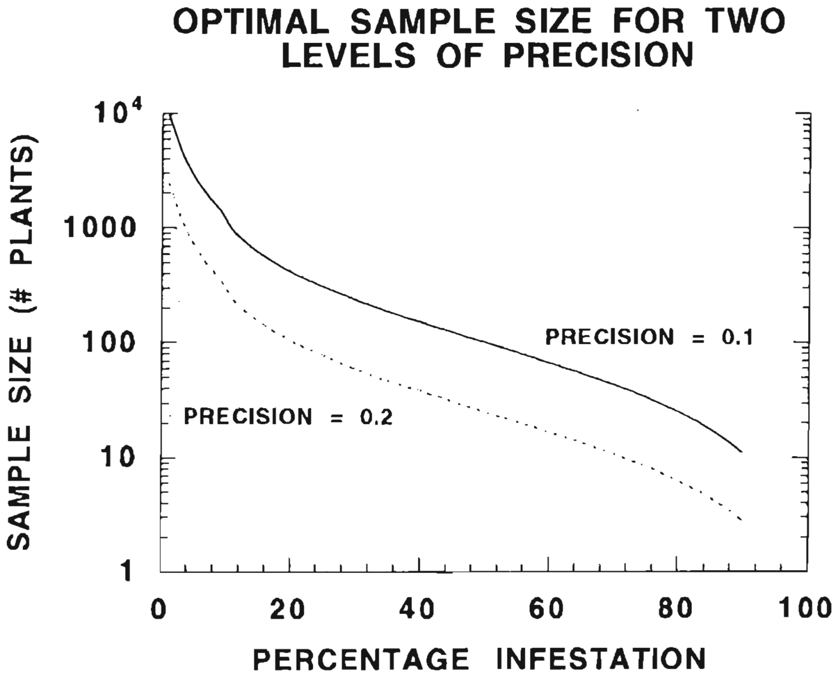


Figure B5. The relationship between percentage infestation in a field and the necessary sample size to estimate the true percentage at two levels of precision.

higher intercept = ln [(1 - α)/β]/ln [(U* (1 - L))/(L * (1 - U))]
lower intercept = ln [β/(1 - α)]/ln [(U* (1 - L))/(L * (1 - U))]
slope = ln [(1 - L)/(1 - U)]/ln [(U*(1 - L))]/(L*(1 - U))]

where:

ln = natural logarithm,
L = lower limit about desired threshold, proportion at which sampler decides the sampled estimate is less than threshold,
U = upper limit about desired threshold, proportion at which sampler decides the sampled estimate is more than threshold,
α = probability of type I error,
β = probability of type II error,

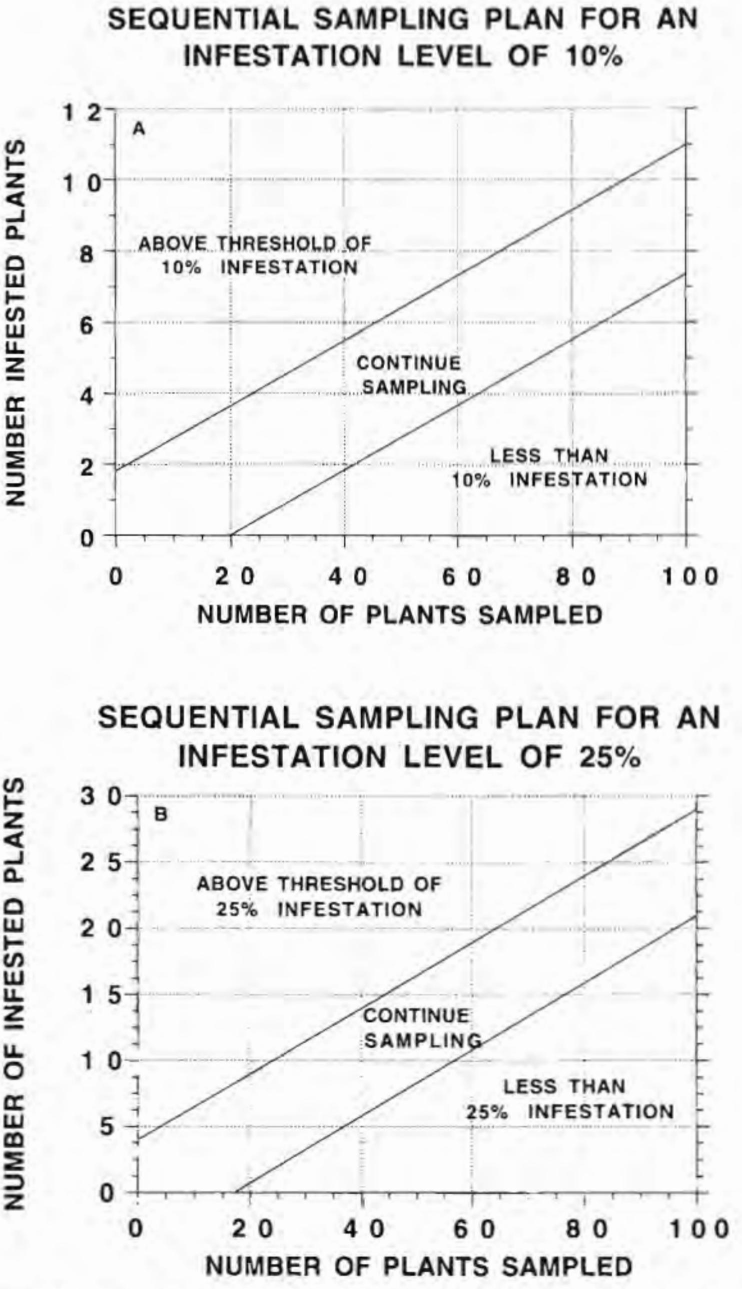
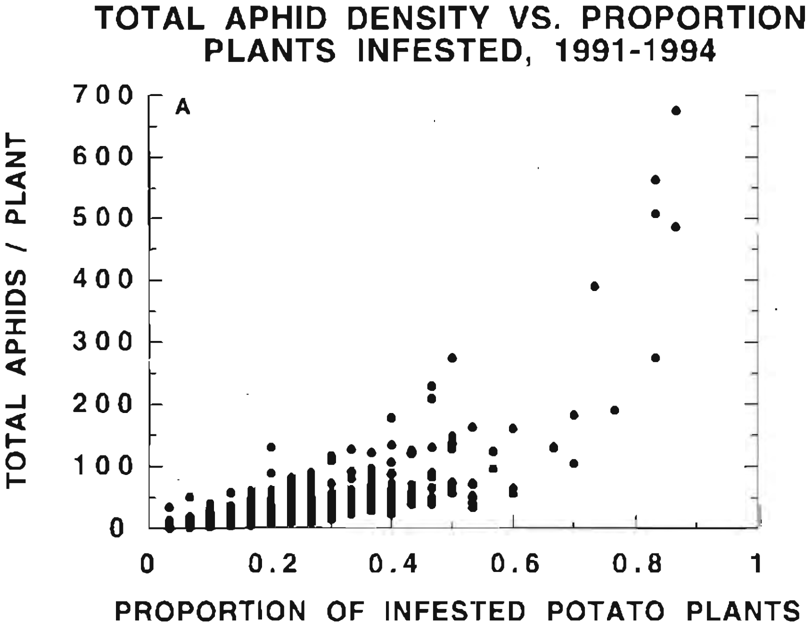
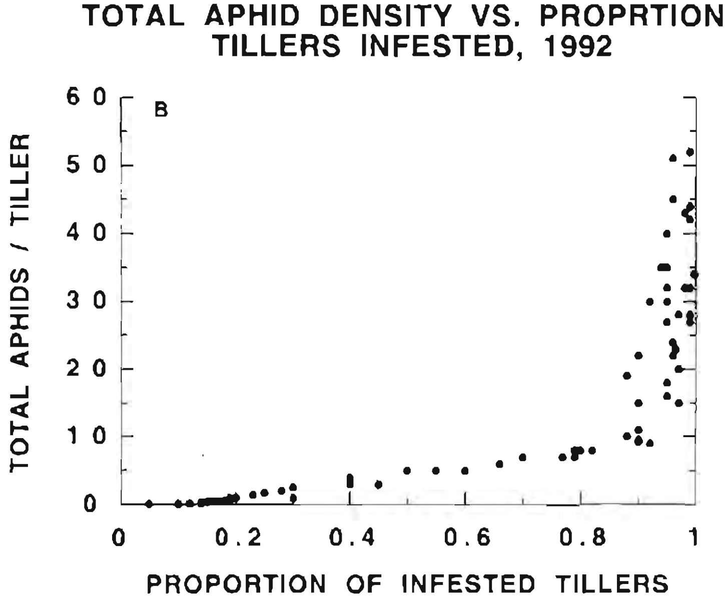


Figure B6. Sequential sampling plans for detecting an action threshold as a function of percentage aphid-infested plants, 10% infested plants (a) and 25% infested plants (b).



TOTAL APHID DENSITY VS. PROPORTION PLANTS INFESTED, 1991-1994



TOTAL APHID DENSITY VS. PROPRTION TILLERS INFESTED, 1992

Figure B7. Relationship between aphid density and the proportion of infested potato plants in 1991–1994 (a) and proportion of infested barley tillers in 1992 (b).

Figure B6a shows a sequential sampling plan for a 10% potato plant infestation threshold (T), a lower limit of 5% infestation (L) and an upper limit of 15% infestation (H). Figure B6b shows a sequential sampling plan for a 25% potato plant infestation threshold (T), a lower limit of 20% infestation (L) and an upper limit of 30% infestation (H). In both sampling plans $\alpha = 0.10$ and $\beta = 0.10$.

The above sampling plans were developed independent of crop, time of year, or location; therefore, they can be used in sampling potato or barley. If it is necessary to estimate the mean number of aphids per plant in a field then a specific relationship must be determined between aphid density and the proportion of infested plants. This relationship may depend upon the aphid species, the crop, stage of the crop, location, and many other factors. To explore the potential of developing binomial sampling plans for estimating aphid density in the Maine potato ecosystem, we used the sampling data for total aphids in barley (1992) and potato (1991–1994). Figure B7a depicts the relationship between total aphid density and the proportion of infested stems for barley and Figure B7b shows the same relationship for potato. In both graphs, the density changes geometrically with increases in the proportion infested and increases most rapidly when the proportion of plants infested increases from 0.70 to 1.00. This relationship is common between aphid species and aphid species complexes (Elliot et al. 1994). The K-S equation is the most commonly used equation to predict insect density from a proportion of infested plants (Jones 1994):

$$\ln(m) = a + b * \ln(-\ln(1-P_t))$$

where:

ln = natural logarithm,
m = density of insect pest (insect/plant),
a = intercept of linear regression,
b = slope of linear regression,
P_t = proportion of infested plants, where infested can be all plants that have more than 0 insects (P_0), or all plants that have more than 1 insect (P_1), or all plants that have more than two insects (P_2), etc.

Table B3 lists the K-S regression coefficients for total aphid densities sampled in barley during 1992 and for the total aphid densities in potato sampled during 1991 and 1994. There were no significant differences between regression equations for the four years in potato. This is an important finding suggesting that the spatial dispersion of the different aphid species in potato is quite

Table B3. Coefficients of K-S regressions representing the relationship between the proportion of infested plants and total aphid density.

Crop	Year	Intercept ± 95% CI	Slope ± 95% CI	r^2
Barley	1992	1.637 ± 0.129	1.631 ± 0.234	0.95
Potato	1991	3.239 ± 0.682	1.174 ± 0.417	0.90
	1992	4.979 ± 0.822	1.312 ± 0.520	0.86
	1993	3.795 ± 0.834	1.183 ± 0.365	0.81
	1994	4.343 ± 0.977	1.235 ± 0.615	0.80
	pooled	4.812 ± 0.778	1.293 ± 0.356	0.86

similar and that a single model can be developed for predicting aphid densities in any given year. Therefore, the potato data was pooled over the four years and a single regression model was determined to describe the relationship between the aphid density and the proportion of potato plants infested. Figure B8a shows the K-S linear regression model for barley and Figure B8b depicts the model for the potato aphid complex. One obvious feature of Figure B8b is that the variation about the regression line is fairly high at low densities, although the total variation in aphid density explained by the proportion of infested plants is 89% (out of a possible 100%). This level of variation should be adequate, on average, for predictions of mean aphid density, but caution should be used at low aphid densities.

The models that we have developed for predicting total aphid density from the proportion of infested plants can be used to calculate optimal sampling plans. For instance, if scouts are sampling the proportion of infested plants to estimate total aphid density, the number of samples necessary for a desired level of precision can be determined using formulae derived by Nyrop and Binns (1992). The optimal sample sizes calculated from their formulae tend to be heavily dependent upon the residual mean square error from the K-S regressions. Therefore, the potato regression that exhibited more variation than did the barley K-S equation results in higher sample sizes in potato than in barley (Figure B9). This difference in sample size is largely because the potato relationship was derived from four years of data while the barley regression was only based upon a single year. Therefore, adoption of the optimal sampling plan for barley should be with caution. The optimal sampling plans developed here are based

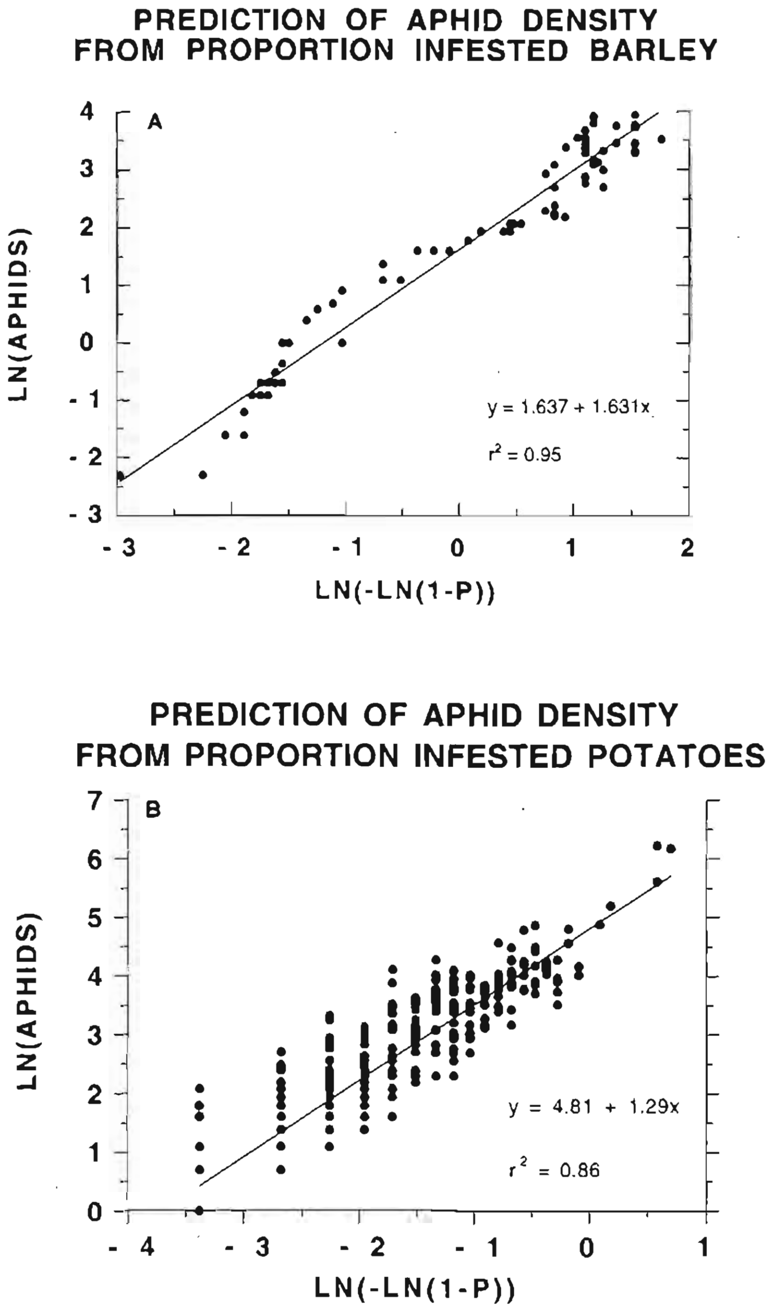


Figure B8. Relationship between aphid abundance (log scale) and the proportion of infested plants or tillers (log-log scale) for barley (a) and potato (b).

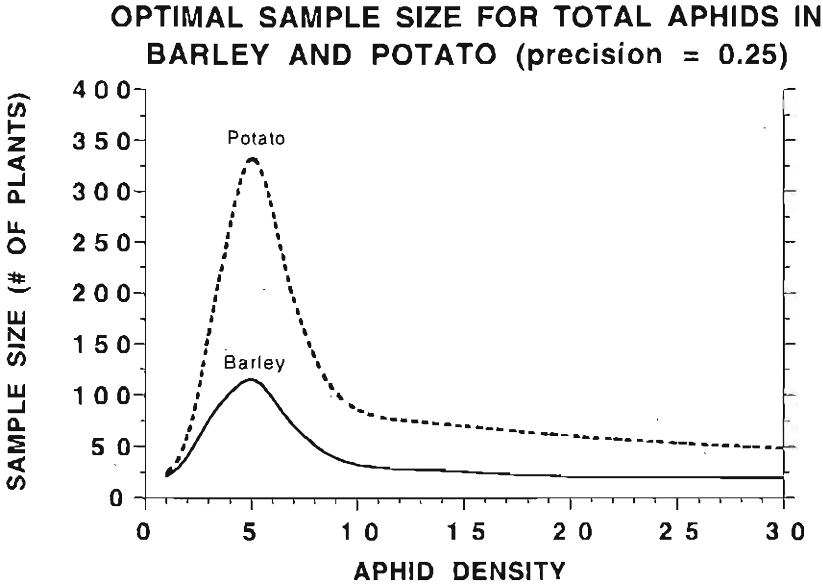


Figure B9. Optimal sample sizes necessary for estimating potato or barley total aphid densities from an estimate of the proportion of infested plants in a field at a precision level of 0.25.

upon a proportion of infested plants with more than 0 aphids on a plant. If one uses a different threshold for determining an infested plant (i.e., more than one aphid on a plant), then the sample size for a given level of precision will usually decrease (Figure B10). However, regression models for these data may not fit the data as well. Additionally, if the threshold is increased, it will take more time in the field to estimate the proportion of infested plants because the scouts will have to carefully count aphid densities up to the threshold density level (Jones 1994). Presently, we are sampling aphids densities in potato because we are interested in describing the population dynamics of the most common species. We have presented sampling guidelines here, however, for a less labor-intensive and more economically efficient approach to estimating aphid infestation in potato.

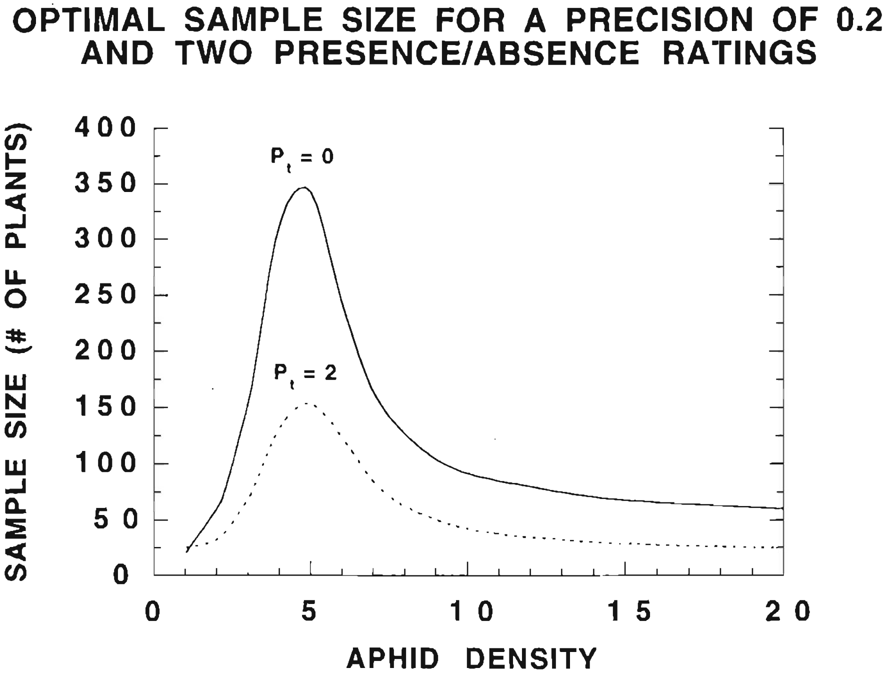


Figure B10. Optimal sample sizes necessary for estimating potato aphid abundance from an estimate of the proportion of infested plants sampled if the proportion infested plants is defined as all plants that have at least one aphid or all plants that have at least three aphids.

GEOSTATISTICS AND KRIGING

In 1993 and 1994, insect and weed sampling in potato was conducted as in the previous two years, except that the east-west and north-south coordinates of each sample in each of the plots was recorded. We accomplished this by numbering each plot row and, within each row, placing flags every 20 feet so that the coordinates could be determined quickly. These data allow the relationship of pest density to be determined between samples at varying distances. From this information, densities of insects or weeds can be estimated at points in the field that were not sampled, based upon the plant locations that were sampled. Various statistical algorithms have been devised to estimate spatial densities based upon these spatially dependent collections of data points; of these, kriging has become the most popular (Cressie 1991). This type of data analysis not only allows field or plot pest density estimates and resulting optimal sample size determination, but also allows the production of spatial maps so that effects of field borders, hedgerows, or soil heterogeneity on pest populations can be investigated. These techniques of spatial data analysis, while they were developed in the geological and mining sciences, now are being investigated for pest management (Russo 1984; Coulson et al. 1988; Liebhold and Elkinton 1989; Kemp et al. 1989; Lecoustre et al. 1989; Gage et al. 1990). Figure B11 shows a map of CPB adult densities in two of our potato plots on 9 June 1993 and 17 June 1993. The pattern of spread into the plot can be detected: the darker areas are the regions of high density. The map shows how adults have initially colonized one corner of the plot. This corner happened to be near a forested border, most likely a source of overwintering beetles. Eight days later CPB adults have spread one-quarter of the way across the plot in relatively high densities. There is a gradual decrease in density as the distance from the initial colonization area increases. Figure B12 shows another series of plots all sampled on 19 July 1993. These maps show the spatial clumping or aggregation of larvae. What is particularly interesting is that the clumping is not at the level of a single plant, but instead the clumps are regions of the plot that consist of many plants. This clumping pattern tends to be characteristic independent of larval density.

Most of our work to date has been to evaluate the performance of kriging for estimating average plot pest insect densities and interpolated spatial distributions. Kriging is a statistical interpolation technique that estimates a density of an unsampled point, x_p, from a weighted linear combination of surrounding points. If $Z(x_p)$ is the estimated density at x_p then:

$$Z(x_p) = \quad w_i Z(x_i)$$

where:

wi = weighting factor at location i, and the weight is proportional to the distance from x_p, the higher weights are given to the points closest to x_p,

$Z(x_i)$ = density at the sampled location i,

To estimate the expected value of each unsampled point, the semivariogram (h^2) must be determined. The semivariogram is essentially a variance of the difference between densities at different sample locations as a function of the distance between them. A semivariogram that has a linear shape and a slope of zero suggests random or uniform distributions, while a semivariogram that is

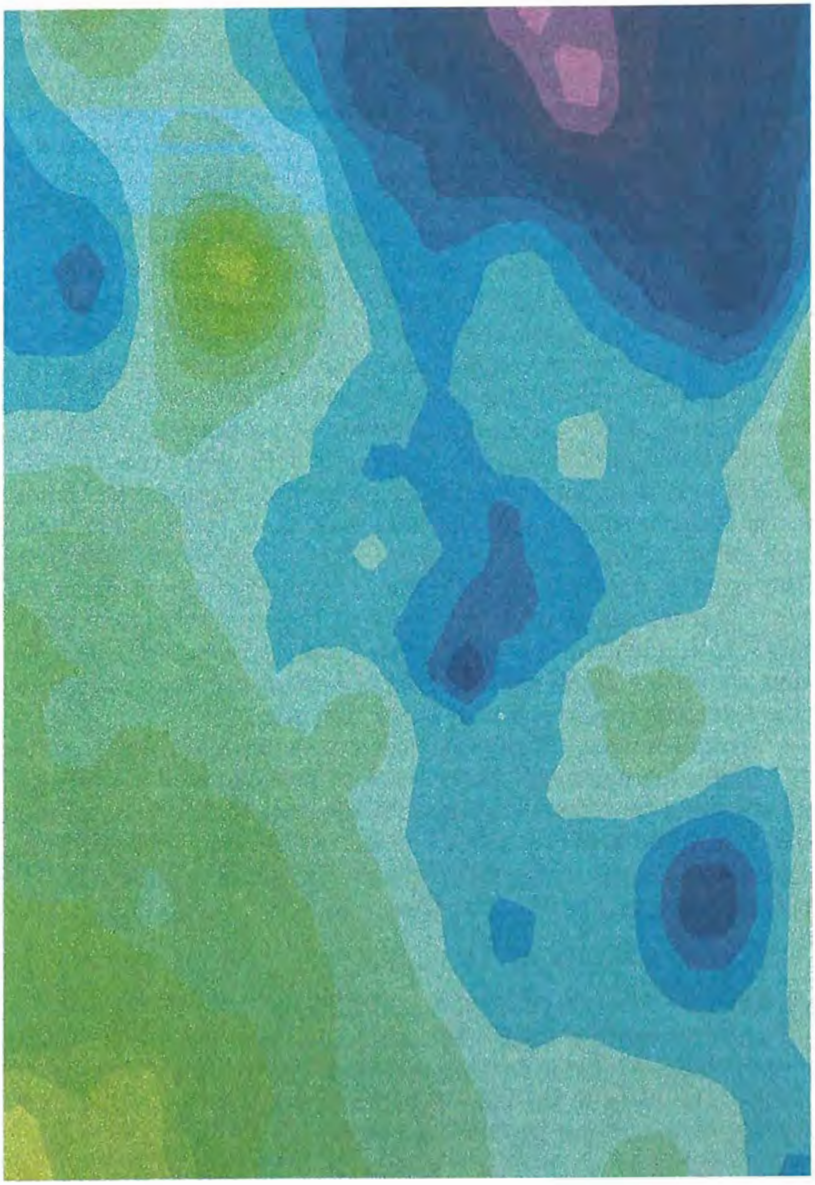


Figure B11a. Colorado potato beetle adult colonization of a potato plot on 9 June 1993. Density is represented as a gradient, red = high density (2 or more adults/plant), orange = next highest, yellow = moderate density, green = low density, blue = very low density (0.1 or less adult/plant), and violet = no adults/plants

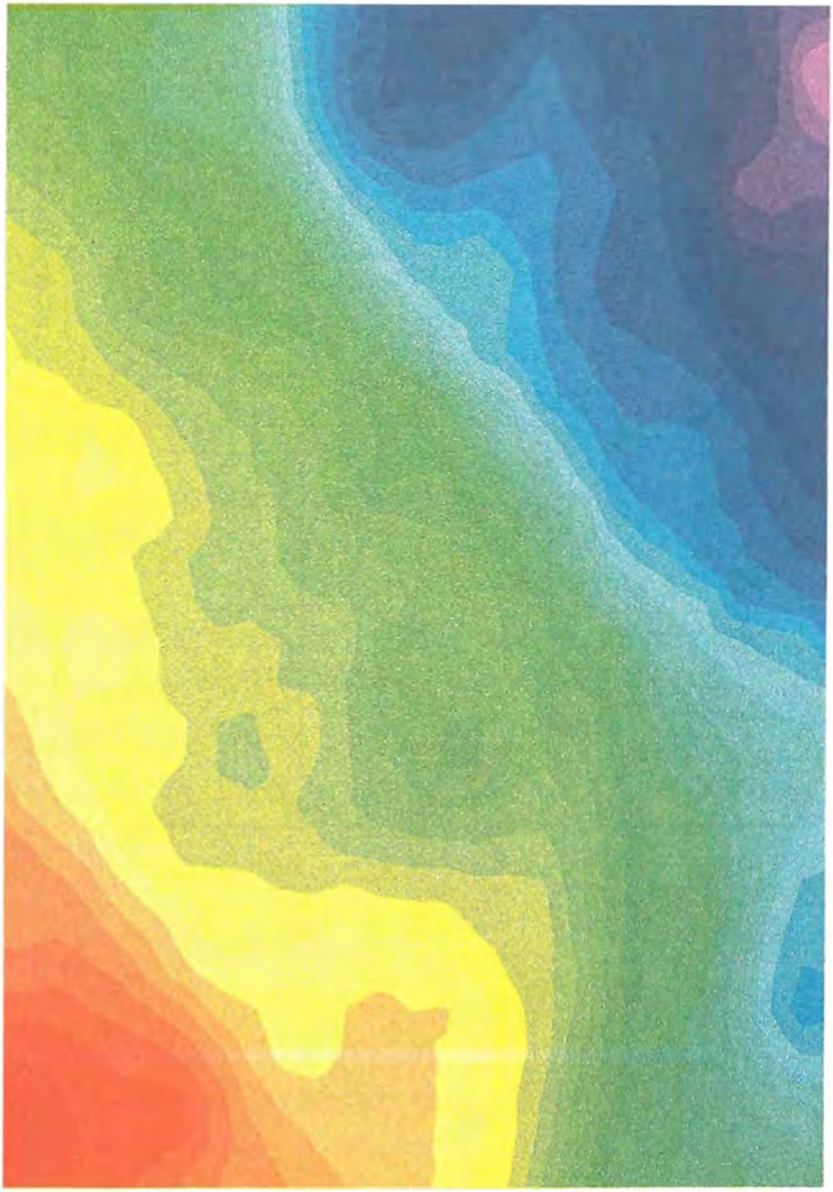


Figure B11b. Colorado potato beetle adult colonization of a potato plot on 17 June 1993. Density is represented as a gradient, red = high density (2 or more adults/plant), orange = next highest, yellow = moderate density, green = low density, blue = very low density (0.1 or less adult/plant), and violet = no adults/plants

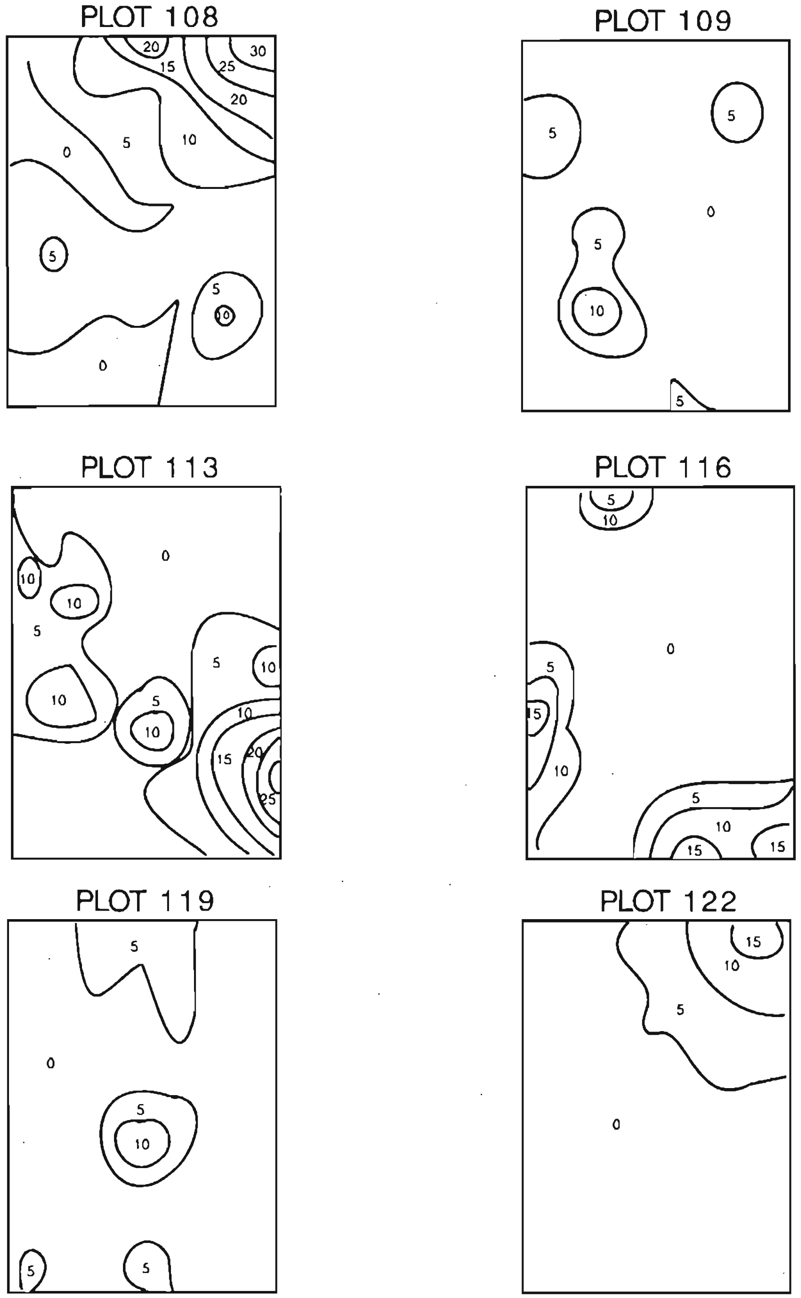


Figure B12. Colorado potato beetle larval spatial pattern within several plots on 19 July 1993. The isolines represent different densities (number of larvae per plant) aggregated within each plot.

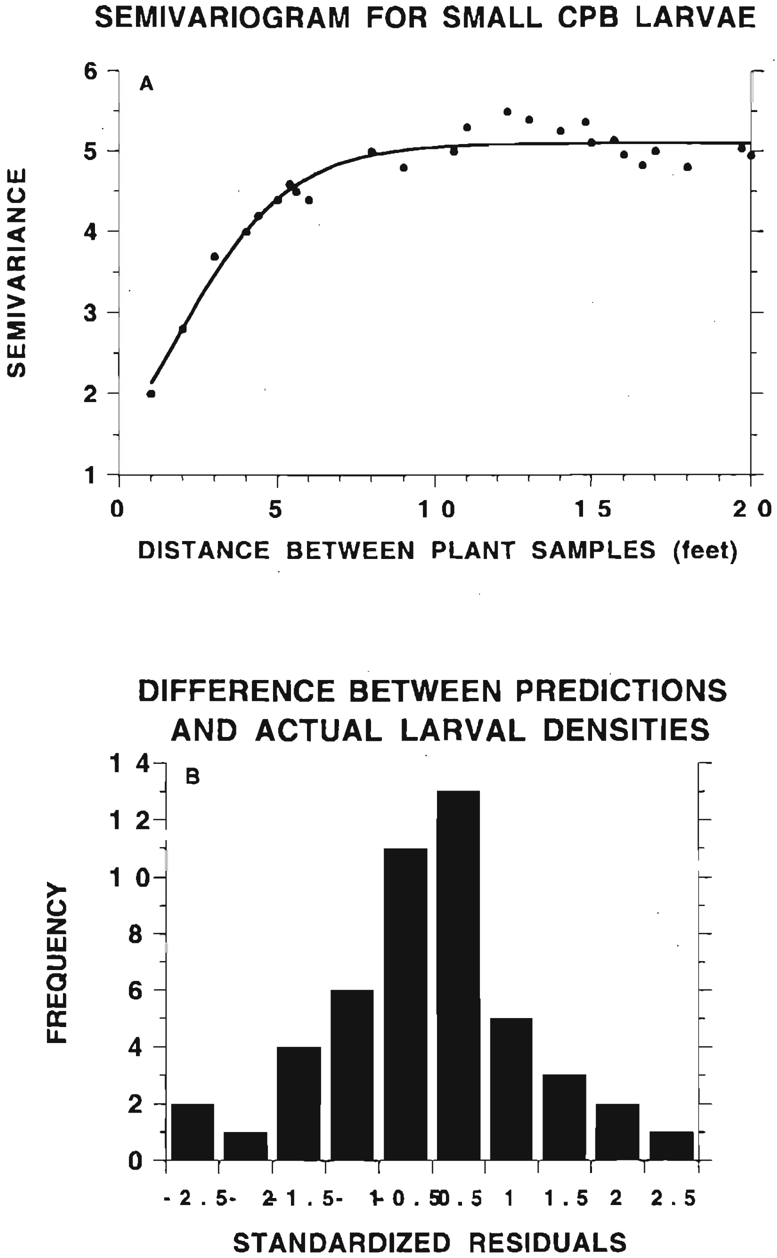


Figure B13. The relationship between spatial pattern (semivariance) of Colorado potato beetle small larvae and the distance between plants within a potato plot (a) and the error (standardized z-scores) between predictions of spatial pattern (based upon the semivariogram model [a]) and the observed sampled spatial pattern of larvae (b).

linear with a positive slope or asymptotic suggests a clumped distribution. Figure B13a depicts a semivariogram for peak density CPB small larvae in 1993. Our semivariogram was produced as a result of block kriging instead of the more commonly used point kriging (Cressie 1991). Block kriging is based on using groups or clusters of plants instead of individual plants to estimate spatial variation. This was necessary in the case of CPB since densities fluctuated too abruptly from plant to plant to use point kriging. The asymptote, or sill as it is called, is the point at a specific distance between samples at which the points are independent of each other (the density at one location is not correlated with the density at another point). The sill is at a distance of 11.6 feet; therefore this is the distance at which larval densities on plants become independent of each other. This confirms the impression, arrived at by inspecting Figure B11, that the clumping of CPB larvae occurs in regions of the plot, not just at the scale of the plant. An analysis of anisotropy (determine if directional effects exist, i.e., down the potato row vs across the row) and cross-validation (Ecker and Heltshe 1994) was performed to test the predictive capability of the estimated semivariogram. Figure B13b shows that, when plotting the difference between the predicted densities and the observed densities standardized by the kriging standard deviation, none of the 48 standardized differences were greater than 3.0. This suggests that errors in prediction were symmetrically distributed about zero and on the average were small.

Kriging can be used to estimate plot means of insect densities. We compared the results of using kriging for estimating CPB density to simple random normal distribution sampling of CPB stage specific densities. Table B4 shows the means and standard deviations for both the kriging and random sampling normal distribution estimates. Kriging performed as well as (standard deviation to mean ratio was similar) random sampling when the number of plants sampled per plot was large (100 or 400 samples per plot). Random sampling, however, was better when the sample size was small (n = 30 or 50 samples per plot). This agrees with the findings of Russo (1984), who suggests that accurate variograms are difficult to estimate with fewer than 100 samples. Therefore, random sampling will offer a slightly greater level of precision for the sample sizes used for the pest management scouting.

Kriging was compared to nonlinear splines and weighted least square regression for prediction of CPB densities where samples were not taken in the plots (between sampled plants). Mean square predictive error (MSPE) was calculated for each method (Ecker and

Heltshe 1994). MSPE is a measure of the robustness of the model to small changes in the data, the lower the MSPE, the better the overall model is at predicting interpolated densities. Table B5 shows that generally the weighted least squares procedure is best for small sample sizes, while kriging is best for large sample sizes. Splines are the worst models for predictions. Laslett (1994) suggests that splines are only suited for spatial patterns that do not change abruptly. Figure B12 suggests that, for the CPB, densities change abruptly from one small part of a plot to another.

Our research into the spatial dynamics of pest has just started. It is apparent from our preliminary analyses that larger-scale sampling experiments need to be conducted so that effects of field borders on spatial dynamics of pests can be accurately estimated. Our future goal is to study the spatial correlation between pests to see if pest outbreaks of one species enhance or limit outbreaks of other pests. For instance, does an increase in lambsquarters

Table B4. Kriging and random sample estimates[1] of plot densities on June 25, 1993.

		Kriging Estimates		Random Sampling	
CPB Life Stage	# Samples[2]	Mean	Std Dev.	Mean	Std. Dev.
Adults	30	0.22	0.53	0.28	0.45
	50	0.26	0.58	0.25	0.38
	100	0.29	0.43	0.26	0.48
	400	0.25	0.41	0.21	0.49
Egg Masses	30	0.14	0.31	0.09	0.22
	50	0.12	0.25	0.15	0.11
	100	0.18	0.42	0.13	0.07
	400	0.14	0.16	0.10	0.14
Small Larvae	30	2.35	2.03	3.13	2.47
	50	3.14	2.97	2.45	2.69
	100	2.77	3.04	2.22	1.98
	400	3.12	2.08	2.67	2.01
Large Larvae	30	0.87	1.21	0.96	1.04
	50	0.99	1.33	1.01	1.21
	100	0.74	1.26	0.82	1.23
	400	0.93	0.98	0.88	0.93

[1] Estimates are based upon the mean from three plots.

[2] Each plot had 533 plants sampled in a uniform grid from which 30, 50, 100, and 400 randomly chosen or systematically chosen (kriging) plants were used to estimate mean and standard deviations of plot mean densities.

Table B5. Comparison between the predictive capability of interpolation (MSPE[1]) by kriging, splines, and weighted least squares.

CPB Life Stage	# Samples[2]	Kriging	Splines	Weighted
Adults	30	0.456	0.567	0.388
	50	0.411	0.505	0.323
	100	0.303	0.512	0.412
	400	0.267	0.464	0.335
Egg Masses	30	0.677	0.795	0.552
	50	0.581	0.654	0.644
	100	0.485	0.522	0.421
	400	0.366	0.429	0.388
Small Larvae	30	0.312	0.344	0.329
	50	0.282	0.287	0.314
	100	0.277	0.322	0.324
	400	0.289	0.345	0.297
Large Larvae	30	0.466	0.522	0.411
	50	0.471	0.488	0.368
	100	0.324	0.388	0.395
	400	0.366	0.345	0.360

[1] Mean square predictive error estimates are based upon the mean from of three plots. MSPE estimates are jackknife estimates of the residual error about a predictive model estimate.

[2] Each plot had 533 plants sampled in a uniform grid from which 30, 50, 100, and 400 randomly chosen or systematically chosen (kriging) plants were used to estimate mean and standard deviations of plot mean densities.

populations result in a concomitant increase in potato aphid populations? Large field-scale studies would also allow us to evaluate the concept of "localized pest management" developed by Fleischer and Smilowitz (1995). This scenario of pest management relies on accurate estimates of spatial maps of potato pests so that only those portions of a field that are above an economic threshold need control measures applied. This concept has promise, and could result in conservation of natural enemies, economic savings, and delay the development of insecticide resistance since areas of a field may persist throughout the growing season without insecticide treatment.

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