SARE Project LNE93-36

SARE Project ANE93-18

ATTACHMENT #1

Project Number: LNE93-36/ANE93.18

Detailed Methods and Results by Objective

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ATTACHEMENT #1 -- DETAILED METHODS AND RESULTS BY OBJECTIVE

Final Report

1. **Project Number:** LNE93-36/ANE93.18
   Grant Number: USDA Cooperative Agreement 91-COOP-1-6593
   University of Maine Accounts (5-6-42484 and 5-6-42488)
   Funding Period: June 1993 to March 1996

2. **Objective 1.** Determine the effect of green manure, compost and manure use on soil physical properties, nitrate leaching, and potato plant growth, water status and yield.

   Objective 2. Determine the impact of two microbial pathogens (*Bacillus thuringiensis* and *Beauveria bassiana*) and two insect predators (*Perillus bioculatus* and *Coleomegilla maculata*), singularly and in combination, on mortality of Colorado potato beetle.

3. Project Results

A1. Detailed Methods and Accomplishments by Objective (Objective 1)

Field Site and Crop Management. Field experiments were conducted during 1993-95 at Aroostook Research Farm, Presque Isle, ME to study the effects of two types of organic soil amendments: 1)an oat, pea, vetch green manure; 2) an amendment program consisting of 22 and 44 Mg ha^{-1} f.w. basis of waste potato compost and beef manure, respectively. Potatoes (cv. 'Superior') were used as the test crop in this experiment. The goals of the crop rotation and soil amendment programs were to improve soil quality and, hence, increase the productivity of the soils for potato production. Three water management treatments (rain-fed check, reduced irrigation, moderate irrigation) were included to determine if these soil management strategies could substitute for supplemental irrigation. Water management treatments were applied as main plots (0.05 ha each) in a split-plot, randomized complete block design experiment with four replications per treatment. Buffer strips were maintained around each main plot to isolate each water management plot from adjacent plots. Subplots (0.0125 ha each) within each main plot were set up to test the two soil management approaches in 2 x 2 factorial combination. This resulted in four subplot treatments: 1) oats, unamended; 2) oats, amended; 3) green manure, unamended; and 4) green manure, amended. These subplots were further split during 1993 and 1994 to compare two rate of nitrogen fertilizer (134 vs. 202 kg ha^{-1})

Two adjacent sites were used for this experiment. Both experimental sites had been cropped to potatoes during 1991. The total experimental area was 1.6 ha with 0.6 ha in potatoes during each growing season. Site #1 was cropped to rotation crop treatments during 1992 and 1994. It was used for the potato test crop during 1993 and 1995. Site #2 was cropped to rotation treatments during 1993 and 1995. It was cropped to oats during 1992 and used for the potato test crop during 1994. The amendments were applied during the spring of every year beginning in 1992 (the year prior to planting the potato crop). Both sites were disked and harrowed immediately after amendments were applied. Crops were planted as soon as possible thereafter. Agronomic practices, dates of field operations, etc. are listed in Table 1-1. Herbicides, fungicides, and insecticides were applied with standard boom-type, tractor-mounted sprayers. Timings, rates, and materials were those generally recommended by the University of Maine Cooperative Extension.

The oat rotation crop subplots were seeded with 108 kg ha^{-1} of 'Porter' oats during each year and received a standard application of 45 kg N ha^{-1} at planting. The green manure subplots were seeded to a mixture of oats, peas, and vetch (54, 168, and 34 kg ha^{-1}, respectively). The green manure crop was inoculated with rhizobium, but was not fertilized. At harvest, the oat grain was removed with a combine and the straw was left on the surface over the winter. The green manure crop was also left to winter on the surface during 1992 and 1993, but incorporated into the soil during fall 1994.

Soil Monitoring Methods. Each spring, soil samples were collected from each plot to a 15-cm depth prior to amendment application. Each sample was analyzed for mineral nutrient content (standard methods, University of Maine Soil Testing Laboratory) and soil organic matter content (Walkley-Black method, Nelson and Sommers 1982). Samples were also periodically collected and analyzed for inorganic nitrogen concentration (KCl extracts, Porter and McBurnie, 1996). Soil physical property measurements included infiltration rate (double ring infiltrometer), bulk density (core method, Blake and Hartge 1986), and soil moisture tension characteristic curves (pressure extraction plates, Klute 1986; Porter and McBurnie 1996). The 1993 bulk density samples were not corrected for stone content; however, stone content was measured in the 1994 and 1995 samples by sieving (>2 mm) coarse materials from each sample. Coarse fragments were weighed and the bulk density without stones was calculated based on stone weight and a measured average density of 2.28 g cm^{-3}. Soil samples were collected prior to tillage each spring for determination of water stable aggregate content using a wet sieve method (Porter and McBurnie 1996). Gypsum blocks (Soil Moisture Equipment Corp., Model 5201) were also installed at the 23 and 46 cm depths. Resistance in relative units was read for each gypsum block with a digital meter (Soil Moisture Equipment Corp., Model 5910A) at regular intervals. Gravimetric moisture samples were collected at regular intervals to provide a measure of soil moisture content by weight. These samples were dried and processed using standard methods.

Nitrate losses were estimated from soil moisture samples collected from four suction lysimeters (2 each @15 and 30 cm depths) installed in the 48 high N fertilizer plots during 1993. Nitrate concentrations in the samples were measured with a nitrate ion selective electrode (ISE) attached to a millivolt meter. Sample collection proved to be so unreliable that these measurements were discontinued during 1994 and 1995.

Runoff collectors were installed in the most uniformly sloped plots of the experiment during August 1994. Similar collectors were installed during July 1995. Two collectors were installed on the down-slope side of each plot with each collecting runoff from non-wheel-track furrows. Sample area per plot was 25.1 m^2. Slopes ranged from 2.9 to 8.8% for the sampled plots. No runoff occurred during the 1994 sampling period; however, runoff was collected on seven dates during July and August 1995. Runoff and sediment data presented represent pooled values for the entire collection period.

Table 1-1 Summary of Agronomic Practices for the 1993-95 Soil Management x Supplemental Irrigation Experiment, Aroostook Research Farm, Presque Isle, ME.

Practice	1993	1994	1995
Previous Crop	oats or green manure	oats or green manure	oats or green manure
Fall Tillage (previous year)	none	none	chisel plow (1X)
Amendment Application	May 28	May 25	May 9 and 10
Amendment Incorporation	May 28	May 25	May 10
Spring Tillage	chisel plow (2X) disk (1X) harrowed (1X)	disked (2X) harrowed (1X)	disked (1X) and harrowed (1X)
Planting Date	June 9	May 31 to June 3	May 26
Seedpiece Spacing	23 cm machine planted	23 cm machine planted	23 cm hand planted
Fertilization banded at planting	134 or 202 kg N ha^{-1} 134 kg P_2O_5 ha^{-1} 134 kg K_2O ha^{-1}	134 or 202 kg N ha^{-1} 202 kg P_2O_5 ha^{-1} 202 kg K_2O ha^{-1}	172 kg N ha^{-1} 172 kg P_2O_5 ha^{-1} 172 kg K_2O ha^{-1}
Herbicides	June 18[1]	June 13[2]	June 7[3]
Pest Control	1X esfenvalerate 3X metalaxyl 8X mancozeb	2X esfenvalerate 1X phosmet 1X methamido-phos 2X metalaxyl 7X mancozeb 4X chlorothal-onil	1X carbaryl 1X methamido-phos 2X azinphos-methyl 6X mancozeb 5X chlorothal-onil
Vine Desiccation	Sept. 16[4]	Sept. 1[4]	August 31[4]
Harvest Date	Oct. 7 and 8	Sept. 22 and 23	Sept. 19 and 20

[1]metribuzin (0.56 kg ai ha^{-1}) applied pre-emergence to the potato crop.

[2]metribuzin (0.56 kg ai ha^{-1}) and paraquat (0.34 kg ai ha^{-1}) plus adjuvant applied pre-emergence to the potato crop

[3]linuron (1.12 kg ai ha^{-1}) applied pre-emergence to the potato crop.

[4]diquat plus adjuvant applied twice, initial application date is listed.

Supplemental Irrigation Treatments. The irrigation system used for this experiment was a small, research-scale system using overhead sprinklers, plastic pipe, and small booster pumps. Supplemental water was applied at a rate of 0.5 cm h^{-1}. The irrigation treatments planned for this experiment consisted of the following three treatments: 1) non-irrigated check; 2) reduced irrigation (fewer or smaller applications than a recommended program); 3) moderate irrigation (with a tuber initiation to mid-bulking goal of maintaining approximately 65% PAW and 0.05 to 0.06 MPa soil tensions). For a variety of reasons, it was not possible to execute these treatments as designed during 1993. Irrigation scheduling during 1993 was conducted based on combined results from tensiometers and gravimetric soil sampling with the general goal of creating treatment differences once the system finally came on line at the end of July. The above management goals were met reasonably well for 1994 and 1995 when gypsum blocks were utilized for scheduling. Total rainfall and supplemental water applications by treatment and year are listed in Table 1-2.

Crop Response Monitoring. Plant height was measured on a weekly basis from early growth until the plants began lying down in the rows. Leaf area and light interception were measured in selected treatments at regular intervals during the growing season using non-destructive means (LAI-2000 Plant Canopy Analyzer, LiCorr, Inc.; Lincoln, NE). Physiological water status was determined in selected treatments at three dates during the 1993-94 growing seasons. Leaf water potential was measured on the upper leaves using a plant water status console (Soil Moisture, Inc; Santa Barbara, CA). Stomatal conductance and leaf transpiration rate were measured as indicators of the degree of stomatal opening and the flow of water from the soil:plant system and into the atmosphere. These measurements were conducted with a steady state porometer (LiCorr, Inc; Lincoln, NE).

Table 1-2 Total June through August water application (cm, rainfall + irrigation) for varied water management programs in the Irrigation x Soil Management Study during 1993 to 1995, Aroostook Farm, Presque Isle, ME. Supplemental water application is listed in parentheses.

Irrigation Treatment	1993[1]	1994[2]	1995[3]
Check	26.8	23.1	16.1
Reduced	32.4 (5.6)	27.6 (4.6)	29.4 (13.3)
Moderate	41.5 (14.7)	32.1 (9.1)	37.4 (21.3)

[1]Initial application was on July 30 and final application was on Sept. 15.
[2]Initial application was on July 18 and final application was on August 20.
[3]Initial application was on July 3 and final application was on August 28.

Yield data were collected from three rows of each subplot. All potatoes from these rows were weighed in the field. Decayed and healthy tubers were weighed separately. One 22-kg sample was collected from each subplot and graded for external defects and tuber size. Samples were taken for hollow heart and brown center evaluations (10 large-sized tubers per sample). Specific gravity was measured with the weight-in-air/weight-in-water method.

Results:

Soil Fertility and Organic Matter. Prior to the initiation of our soil management treatments there were no major differences in soil fertility among the plots (data not presented). Results of soil mineral analyses conducted during 1993 and 1995 are presented in Tables 1-3 and 1-4. Since the soil samples were collected in the spring prior to amendment application, the 1993 data represents the effects of a single amendment application, while the 1995 data represents the effects of three applications. Response patterns for the 1994 soil tests are not presented, but were similar to the 1995 data. After only a single year of application, the amendment treatments had produced significant increases in apparent cation exchange capacity, potassium, magnesium, and calcium levels (Table 1-3). Concentrations of all mineral nutrients, including phosphorus, had been significantly increased by the amendments after two (data not shown) and three years of application (Table 1-4). These effects were expected since the soil amendments (manure and compost) are good sources of these nutrients. Crop rotation did not significantly affect any of these soil properties. Soil amendment application increased soil organic matter concentrations during all three years of the study (Figure 1-1). There were no significant differences in soil organic matter concentrations among the crop rotation treatments.

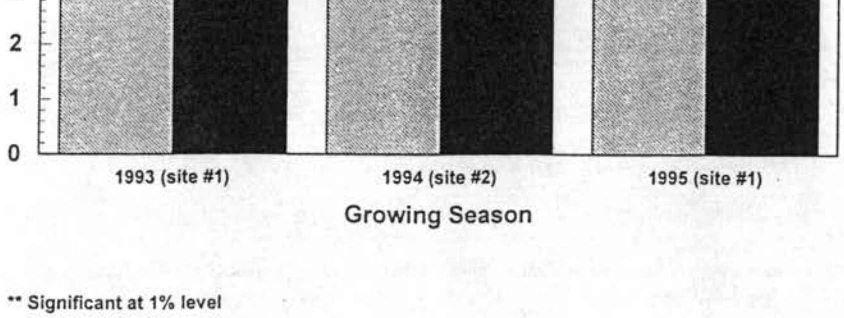


Figure 1-1 Soil amendment effects on soil organic matter content.

Limited inorganic N sampling of the surface soil during 1993 and 1994 indicated that the green manure rotation crop significantly increased soil nitrate concentration (e.g. 59.7 vs. 50.4 mg kg-1 during 1993), but that the soil amendment treatments had no significant effects on soil inorganic N (data not shown). Soil nitrate and ammonium concentrations during the 1995 growing season are presented in Figures 1-2a and 1-2b, respectively. As was expected, the green manure crop significantly increased soil nitrate levels within the soil as it decomposed. The inorganic N data were only collected in the non-irrigated plots. Soil nitrate concentrations accumulated to unusually high levels during 1995 due to the low rainfall. Plant growth and uptake of N would be expected to be dramatically restricted in these plots due to low soil moisture. The amendment treatments significantly increased soil nitrate levels through 70 days after planting during 1995. The crop rotation and soil amendment treatments had very little effect on ammonium concentrations within the soil. Attempts to quantify nitrate leaching with suction lysimeters failed during 1993 and 1994 due to soil heterogeneity and inconsistent sample volumes. We therefore shifted our emphasis to measuring inorganic N in the surface soils during 1995.

Soil Physical Properties. Soil moisture content was monitored in this study with gypsum blocks and by gravimetric sampling. Gypsum blocks were used effectively during 1994 and 1995 to monitor soil moisture levels among the water management treatments and to schedule irrigation applications. Soil moisture levels were nicely separated among the three irrigation treatments during 1994 and 1995 (data not shown). Irrigation treatments began very late during the 1993 growing season and established differences among treatments only during August (data not presented).

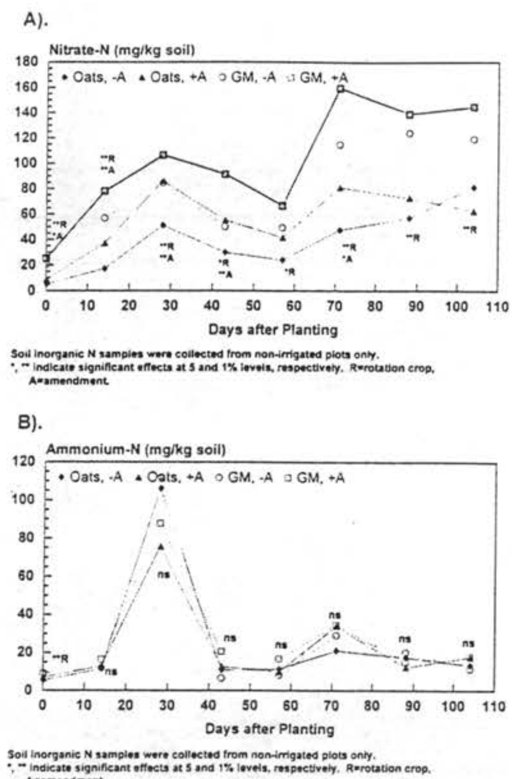


Figure 1-2 Soil inorganic N concentrations during 1995 as affected by rotation crop and amendment application. A) nitrate-N; B) ammonium-N.

Table 1-3 Soil analysis results for the 1993 Irrigation x Soil Management Experiment (after one year of amendment application, Site #1).

Soil Property	Unamended	Amended	Amendment Effect[1]
pH	5.3	5.4	ns
Organic Matter (%)	3.22	3.81	**
Phosphorus (kg ha^{-1})	25.4	25.1	ns
Potassium (kg ha^{-1})	236	304	**
Magnesium (kg ha^{-1})	235	258	*
Calcium (kg ha^{-1})	950	1086	*
CEC (meq $100g^{-1}$)	3.9	4.3	**
Potassium (% Sat.)	7.0	8.2	**
Magnesium (% Sat.)	22.2	22.2	ns
Calcium (% Sat.)	53.3	56.0	ns

[1]Based on analysis of variance: ns=no significant effect; * and ** indicate significant effect at $p<0.05$ and 0.01, respectively.

Gravimetric moisture sampling was used to characterize the effects of soil management treatments on soil moisture content through each growing season. Irrigation treatment and the use of soil amendments dramatically affected gravimetric soil moisture content in this series of experiments. Rotation crop treatments generally did not affect soil moisture content. The effect of soil amendment treatment on 1995 soil moisture content is presented in Figure 1-3. Soil amendment significantly increased soil moisture content at most sample dates. Averaged over the crop rotation and irrigation treatments, the water content of the amended soils was typically about 10% higher than that of unamended soils. Note that the effect of soil amendment on soil moisture content is more pronounced in the irrigated treatments that in the non-irrigated check plots. One explanation for this effect is that the organic amendments dramatically increase the soil's ability to hold moisture upon rewetting, but that the larger plants present in the amended plots utilize this extra moisture fairly quickly and draw the soil moisture content back down to levels experienced in the unamended treatments. The observed changes in soil moisture content confirm that organic amendments can increase the ability of northern Maine soils to hold water. This effect may be beneficial under conditions of moisture deficit; however, it is possible that increased soil moisture might be undesirable when excess rainfall or irrigation takes place. Alternatively, improvements in soil structure could enhance aeration and partially compensate for this effect.

Soil moisture retention characteristics were studied to determine if the soil management treatments would have detectable effects on moisture release characteristics of the soil.

Table 1-4 Soil analysis results for the 1995 Irrigation x Soil Management Experiment (after three years of amendment application, Site #1).

Soil Property	Unamended	Amended	Amendment Effect[1]
pH	5.4	5.6	**
Organic Matter (%)	3.74	4.94	**
Phosphorus (kg ha^{-1})	37.4	42.5	**
Potassium (kg ha^{-1})	298	551	**
Magnesium (kg ha^{-1})	429	524	**
Calcium (kg ha^{-1})	1366	1906	**
Zinc (kg ha^{-1})	0.91	1.28	**
CEC (meq $100g^{-1}$)	5.7	7.2	**
Potassium (% Sat.)	6.1	8.9	**
Magnesium (% Sat.)	27.7	26.8	ns
Calcium (% Sat.)	52.8	59.0	**

[1]Based on analysis of variance: ns=no significant effect; * and ** indicate significant effect at $p<0.05$ and 0.01, respectively.

Summary data from these measurements are presented in Table 1-5. From these laboratory data, we were not able to detect dramatic effects of the soil management treatments on soil moisture retention. This contradicts the soil moisture data collected in the field which indicates that the amended soil has a higher moisture content at most sample dates. Our inability to detect significant differences in the laboratory may partially be due to difficulties in quantitatively comparing the moisture retention curves from a limited number of samples. The gravimetric moisture samplings that were conducted in the field can be conducted quickly enough that several treatments could be compared with sufficient sample size to detect treatment effects even though the soils are quite variable.

We were not able to detect any significant effects of soil management on steady-state infiltration rate (data not shown). The average infiltration rate for this site was 2.52 cm h^{-1} in the furrows and 19.66 cm h^{-1} on the row tops. No effects of soil amendment were apparent from these variable measurements. Infiltration rates in the row tops ranged from 4.56 to 48.0 cm h^{-1} for unamended soils and 3.60 to 71.7 cm h^{-1} for amended soils. In general, we would expect that the organic amendments would improve soil structure, reduce bulk density, and increase rate of water infiltration. The effects on infiltration rate may have been present, but undetectable with the tools that we had available for use in a spatially heterogenous potato field. The soil is naturally quite variable and potato hilling increases this problem. Obtaining adequate sample size to detect significant differences was a problem for our double ring infiltrometer method. The procedure is slow and is quite disruptive to the integrity of the research plots.

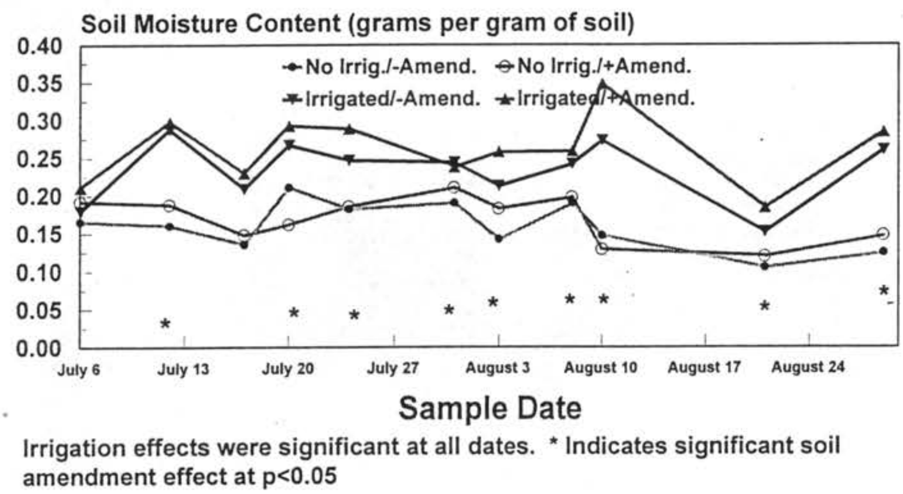


Figure 1-3 Irrigation and soil amendment effects on gravimetric moisture content during 1995.

Soil bulk density data are presented in Table 1-6. All values fell within the standard bulk density range for this soil type (1.00 to 1.25 g cm^{-3} in the upper 30 cm of soil profile, stones included). There were no differences among the irrigation or rotation treatments during any year of the study. There were no measurable effects of the soil management on bulk density during 1993. By 1994, the bulk densities tended to be lower in the amended treatments; however, the effects were not statistically significant. We were able to detect significant reductions in soil bulk density after three years of amendment application (Table 1-6). The decline in bulk density suggests that aggregation of the soil particles has been improved by the organic amendments and that the soil is less likely to become compact and poorly aerated. Crop rotation did not significantly affect soil bulk density in these studies.

Water stable aggregate content of the soil, a measure of soil structure and the stability of soil aggregates, was significantly increased by the soil amendment treatments during 1993-95 (Table 1-7). Soil amendments increased the diameter of the aggregated soil particles. No differences in water stable aggregate content of the soil were detected among the irrigation and crop rotation treatments.

Table 1-4 Summary of soil moisture retention characteristics (g water g^{-1} of soil) for soils subjected to varying soil management treatments.

Soil Management Treatment	Field Capacity	Permanent Wilting Point	Available Water
1993:			
Grain	0.217 (0.200 to 0.235)	0.109 (0.085 to 0.130)	0.108 (0.085 to 0.135)
Grain+Amend.	0.225 (0.200 to 0.245)	0.112 (0.080 to 0.135)	0.113 (0.085 to 0.135)
Green Manure (GM)	0.220 (0.195 to 0.245)	0.103 (0.080 to 0.135)	0.116 (0.085 to 0.165)
GM+Amend.	0.228 (0.210 to 0.255)	0.112 (0.080 to 0.150)	0.116 (0.085 to 0.160)
1994:			
Grain	0.277 (0.240 to 0.300)	0.120 (0.105 to 0.145)	0.157 (0.120 to 0.195)
Grain+Amend.	0.291 (0.250 to 0.325)	0.136 (0.120 to 0.150)	0.155 (0.115 to 0.205)
Green Manure (GM)	0.280 (0.240 to 0.310)	0.128 (0.105 to 0.170)	0.152 (0.110 to 0.200)
GM+Amend.	0.291 (0.240 to 0.325)	0.125 (0.110 to 0.140)	0.166 (0.115 to 0.210)

Runoff and Soil Erosion. Runoff did not occur during the August 1994 measurement period; however, runoff was collected from seven events during July through August 1995. Pooled runoff values were calculated for the entire collection period. Averaged over the 12 plots, runoff was 86.03 ml m^{-2} (SE=8.32) and sediment collection was 1.67 g m^{-2} (d.w. basis, SE=0.48). These data indicate that very little sediment movement occurred from the plots during this portion of the growing season. This result is not surprising given that the potato crop provided considerable ground cover during July and August. Irrigation significantly increased runoff volume [55.47 ml m^{-2} (-I) vs. 101.31 (+I), $p<0.0025$], but did not affect sediment amount [1.56 g m^{-2} (-I) vs. 1.74 (+I), $p<0.74$]. Amendment application did not significantly affect runoff volume [94.67 ml m^{-2} (-A) vs. 68.74 (+A), $p<0.15$] or sediment amount [1.95 g m^{-2} (-A) vs. 1.12 (+A), $p<0.096$]. Statistical tests among the individual soil management strategies were not possible due to the small number of plots for which data could be collected. Runoff volume and sediment amount were not significantly correlated with the slope of the plot ($r=-0.498$ and 0.003, respectively). More precise measurement of soil management effects on runoff and erosion are

Table 1-6 Soil bulk density (g cm^{-3}) within the Irrigation/Soil Management Experiment.

Soil Management	August 1993	May 1994	July 1994	May 1995	June 1995
Grain	1.15	1.26	1.15	1.23 (0.98)	1.22 (0.96)
Grain +Amend.	1.12	1.26	1.08	1.13 (0.87)	1.16 (0.86)
G. Manure	1.17	1.25	1.11	1.20 (0.96)	1.26 (0.98)
G. Manure +Amend	1.16	1.20	1.03	1.17 (0.89)	1.13 (0.84)
ANOVA	NS	NS	NS	Amend $p<0.08$ (*Amend)	*Amend (**Amend)

Numbers in parentheses indicate bulk density corrected for stone content.

Table 1-7 Water stable aggregate content (% d.w. basis) of the soil within the Irrigation/Soil Management Experiment.

Soil Management	May 1993 Site #1	May 1994 Site #2	May 1995 Site #1
Grain	34.5	31.9	36.7
Grain +Amend.	41.7	42.0	43.7
G. Manure	33.1	29.9	39.1
G. Manure +Amend	38.7	39.8	43.1
ANOVA	**Amend	**Amend	**Amend

needed than those provided in this study. In addition to growing season measurements conducted here, runoff measurements should be conducted during spring and fall, since these are periods when runoff will be greatest. Better control of the sampling areas is needed (e.g. more uniform slopes, use of rainfall simulators) to generate reliable data.

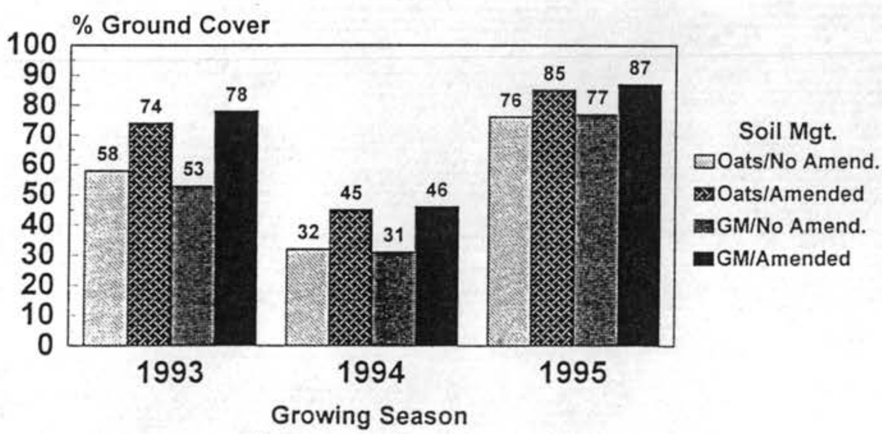
In addition to the direct measurements of runoff and erosion presented above, the general effects of soil management on soil erosion can be explored using the RUSLE equation (Renard et al. 1991; Soil & Water Conservation Society 1993). We have demonstrated that the soil amendment treatments increased soil organic matter content and aggregation. In addition, bulk density of the surface soil has been decreased. These soil changes would be expected to affect soil erosion through effects on the soil erodibility factor, K_f. We do not anticipate that the two rotation crop alternatives would dramatically affect soil erosion as they were managed in this project. This is because both crops provided soil cover for approximately the same growth duration and because the green manure rotation crop did not significantly affect soil organic matter, bulk density, and aggregation when compared to the oat rotation crop. We used the following RUSLE estimates to demonstrate the effects of soil management on soil erosion: R=60 for Caribou, ME; K_f =0.243 (initially from USDA soil erodability nomograph, seasonally adjusted K_f for a Caribou loam soil with 3% organic matter, fine granular structure, moderate permeability, 57% silt and very fine sand, 27% other sands, 10% surface cover with rock fragments); LS=1.01 (300 ft slope at 5% grade); C=0.155 (averaged over the two-year rotation); and P=1.0. Based on these values, RUSLE's estimated annual soil erosion rate for the two-year rotation was 2.28 tons A^{-1} $year^{-1}$. Increasing soil organic matter content by 1% would decrease the seasonally adjusted K_f to 0.216 and annual erosion to 2.03 tons A^{-1} $year^{-1}$. Beyond the increase in soil organic matter, an improvement in the soil permeability class (something that we were not able to quantitatively document in this study) would decrease the seasonally adjusted K_f to 0.198 and annual erosion to 1.85 tons A^{-1} $year^{-1}$. While these effects are relatively small, they do provide evidence that the soil amendment program studied within this project should result in reduced rates of soil erosion.

Potato Crop Growth. Final crop stands were equal for all treatments over the course of this three year study (data not shown) and were very near target plant populations (88, 86, and 96% for the three respective years). Early-season growth of the potato crop was strongly enhanced by the amendment treatments (Figures 1-4 to 1-6). There was no effect of rotation crop or water management treatment on early-season growth. The latter was expected because irrigation application was not initiated until after tuber initiation. Crop height was increased by the amendment treatments during 1993 and 1994 (Figure 1-7), but was not affected during 1995 (data not shown)

Rotation crop and nitrogen rate strongly influenced foliage color and vine maturity in this study (data not shown). Both treatments were designed to manipulate the nitrogen nutrition of the potato crop and the color and vine maturity responses were consistent with the expectation that the green manure crop and higher N rate would deliver considerably more N to the potato crop. The organic soil amendment treatment had only small effects on foliage color and vine maturity.

Foliar late blight was very well controlled in this experiment during 1994 and 1995; however, an outbreak of the disease occurred during September 1993. Inoculum from severely infested fields in the surrounding area resulted in obvious foliar symptoms during the two weeks prior to vine desiccation. We kept the foliage alive with an aggressive spray program, but were never able to completely "dry up" the infection prior to vine desiccation. The blight infection, when combined with excessive rainfall in early September and the pre-existing high soil moisture levels due to August irrigation, resulted in severe tuber decay problems during 1993.

Plant Water Status. Leaf water potential (LWP), stomatal conductance, and transpiration rates were measured on selected dates during 1993 and 1994 to document management effects on plant water status. LWP data were collected on two dates during 1993 (August 13 and 29). The soil amendment programs had no significant effect on LWP during either day (data not shown). LWP data were collected on five dates during 1994. Samples were collected at various times of the day; however, data are presented only for LWP measurements conducted early in the day when the crop should be at equilibrium with the soil (Table 1-8). Irrigation significantly affected August LWP values during 1994 and resulted in LWP values closer to zero than non-irrigated plots. The soil amendment treatments did not significantly affect LWP. Treatments did not significantly affect the non-equilibrium LWP values (data not presented). The equilibrium data indicate that the LWP technique was able to detect reductions in plant water stress associated with irrigation treatments, but that soil amendment effects were not present on these sampling dates. The LWP measurements, therefore, do not provide convincing evidence that the late-season plant water status had been enhanced by the soil amendment treatments. It is possible that the timing of measurements did not capture time periods when the effects of soil amendment on LWP was present. Another possible explanation is that the soil amendment treatments had no effect on plant water status. This seems unlikely given the significant effects that were observed on soil moisture content. An alternative explanation is that plant water status effects show considerable temporal variation. Effects may have been present that could not be detected with our methods



Amendment effect was significant during all three growing seasons

Figure 1-4 Percent ground cover at selected rating dates as affected by soil management treatments (Superior variety).

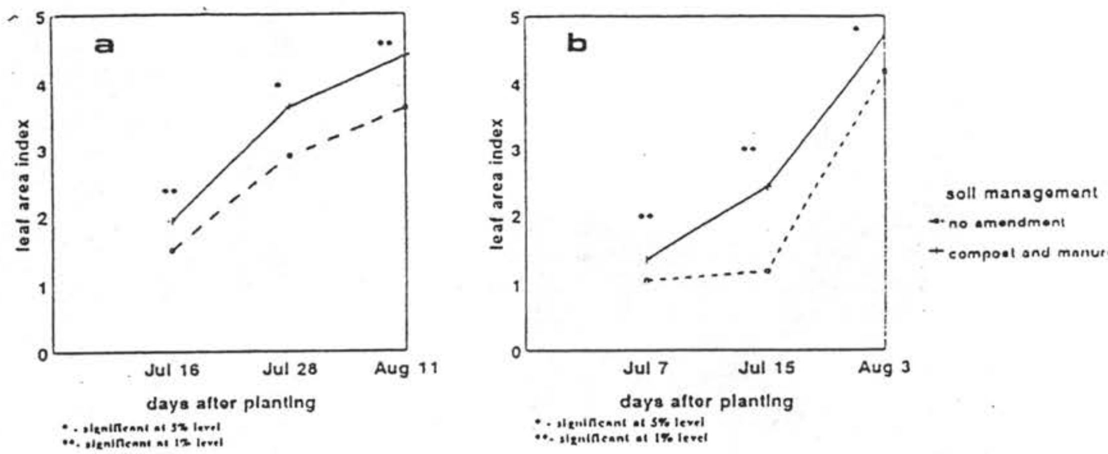


Figure 1-5 Leaf area index (LAI) at selected sampling dates as affected by soil management (Superior variety). A) 1993, B) 1994.

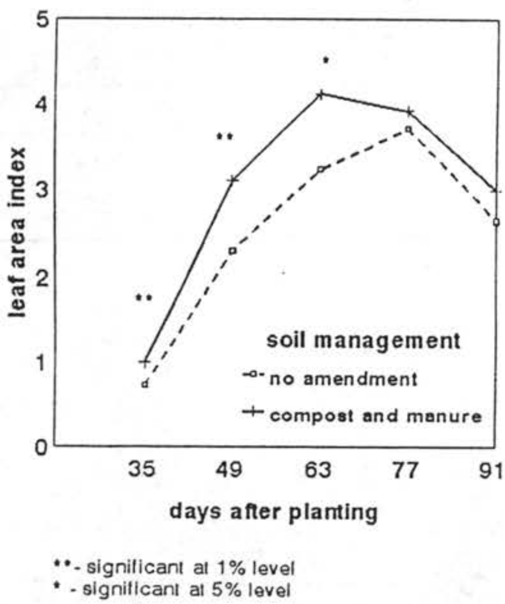


Figure 1-6 Leaf area index (LAI) at selected 1995 sampling dates as affected by soil management (Superior variety).

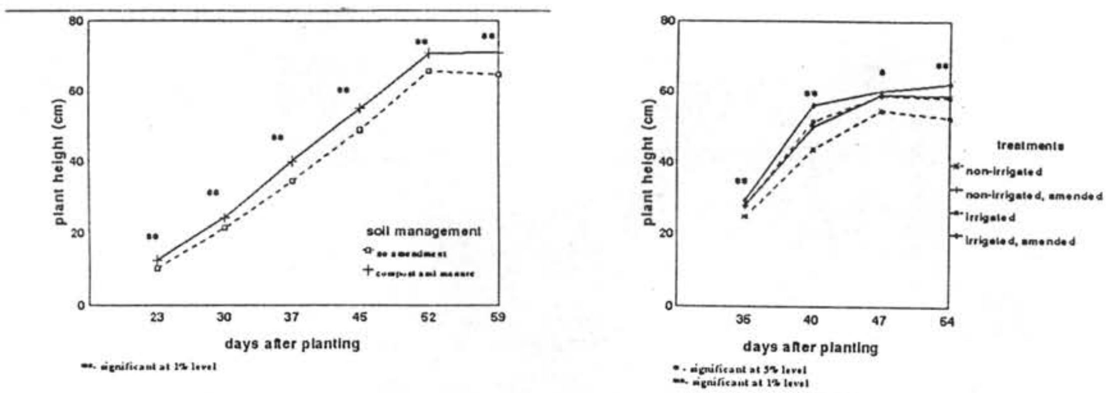


Figure 1-7 Plant height at selected dates as affected by soil management treatments (Superior variety). A) 1993; B 1994.

Table 1-8. Leaf water potential as affected by irrigation and amendment (1994).

Treatments	Leaf water potential (-MPa) July 15[1]	August 10[2]	August 11[3]
Irrigation:			
non-irrigated	0.28	0.44	0.34
irrigated	0.27	0.33	0.16
Amendment:			
no amendment	0.28	0.39	0.25
compost and manure	0.28	0.38	0.25
ANOVA Results:			
Irrigation	NS	*	**
Amendment	NS	NS	NS
Irrigation*Amendment	NS	NS	NS
correlation vs time	0.90**	0.78**	0.13[NS]

[1] - measurements done from 5:30-7:30 AM
[2] - measurements done from 4:30-7:00 AM
[3] - measurements done from 5:00-6:00 AM
[NS] -not significant, * -significant at 5% level
** -significant at 1% level

and limited sampling. Additionally, greater water use by the larger crop canopy within the amended treatments may quickly draw soil moisture levels down to those of the unamended treatments unless moisture is re-supplied via rainfall or irrigation.

Stomatal conductance and leaf transpiration rate data were collected during late August and early September of 1993. No significant differences among treatments were detected (data not shown). Similar measurements were conducted over four dates during 1994 (Table 1-9). Treatments did not affect conductance or transpiration on July 20 or August 11; however, the soil amended plots had significantly higher leaf transpiration rates than unamended plots on July 21 and August 4. These results indicate that plant water use and status of the amended plots was enhanced during this part of the growing season.

Yield and US#1 Yield. The effects of the irrigation and soil management treatments on yield and tuber quality are presented in Tables 1-10 to 1-12. Nitrogen response data will be discussed, but not presented in the tables. Soil amendment treatment and nitrogen rate were the two main effects that significantly affected yield during 1993 (Table 1-10). There were no significant interactions among irrigation, soil amendment, and rotation crop. Soil amendment treatments increased total yield by 8.62 t ha^{-1} (23%), averaged over all levels of water management, and by 8.18 and 9.74 t ha^{-1} for non-irrigated and irrigated conditions, respectively (Figure 1-8). The higher N rate increased total yields by 1.57 t ha^{-1}, relative to the lower rate. Irrigation and crop rotation effects were not significant during 1993; however, we did observe significant interactions between N and amendments, as well as between N and irrigation. The response to N was significantly higher in the unamended plots (3.47 t ha^{-1}) than the amended plots (-0.34 t ha^{-1}). The crop responded to N when no irrigation was used (1.79 t ha^{-1}) and in the reduced irrigation program (3.92 t ha^{-1}), but not in the moderate irrigation treatment (-0.90 t ha^{-1}). Surprisingly, no intereactions between N and rotation crop were detected. The non-significant effect of irrigation was likely a result of the relatively high rainfall received during 1993 and the relatively late application of the supplemental irrigation treatments. Irrigation treatments significantly reduced U.S.#1 yields during 1993 (Table 1-10; Figure 1-9). This was due to the high incidence of decayed tubers that had to be graded out within the irrigation treatments . U.S. #1 yield loss for the moderate irrigation treatment amounted to 11%, while the excess irrigation treatment reduced U.S. #1 yield by 36%. Despite causing a slight increase in percent rot, the soil amendments increased U.S. #1 yields by 3.25 t ha^{-1} (15%) averaged over treatments. The beneficial effect of soil amendments on US#1 yields was similar in irrigated versus non-irrigated plots. Rotation crop and nitrogen rate did not significantly affect US#1 yields; however there was a significant interaction between N and amendment application, as well as between irrigation, nitrogen, and crop rotation. U.S.#1 yields increased in response to the higher N rate in the unamended plots (3.36 t ha^{-1}), but not when amendments were used (-0.90 t ha^{-1}). The US#1 yield response to N was quite similar among the irrigation, nitrogen, and crop rotation combinations (average response over five of the treatments, +2.33 t ha^{-1}) except for the oat rotation crop at the high rate of irrigation (-4.70 t ha^{-1}). Contrary to expectations, US#1 yields at the lower N rate were not higher in the green manure crop rotation (30.4 t ha^{-1}) than the oat rotation (32.4 t ha^{-1}).

The soil amendment, irrigation, and nitrogen rate treatments significantly affected yield during 1994 (Table 1-11). For yield and US#1 yield, there were no significant interactions among irrigation, soil amendment, and rotation crop. August was very dry during 1994 and supplemental irrigation greatly enhanced plant growth and late-season foliage vigor. Irrigation increased yields by 9.63 t ha^{-1} (39%) without amendments and by 10.42 t ha^{-1} (33%) when amendments were applied (Figure 1-8). Soil amendment treatments increased total yield by 8.18 t ha^{-1} (28%), averaged over all levels of water management, and by 6.83 and 7.62 t ha^{-1} for non-irrigated plots and the highest level of irrigation, respectively (Figure 1-8). The higher nitrogen rate significantly decreased total yields by 2.46 t ha^{-1} relative to the lower rate. Crop rotation effects were not significant during 1994 and, contrary to expectations, yields at the lower N rate were not higher following the green manure rotation crop (34.3 t ha^{-1}) compared to the oat crop (35.5 t ha^{-1}). Apparently, 134 kg N ha^{-1} was sufficent N for yield maximization on this site even when oats were the previous crop. Soil amendment and irrigation treatments significantly increased U.S.#1 yields during the relatively dry 1994 growing season (Table 1-11). Irrigation increased U.S. #1 yields by 9.30 t ha^{-1} (36%) averaged over all other treatments. The soil amendments increased U.S. #1 yields by 7.84 t ha^{-1} or 29% averaged over treatments. The beneficial effect of soil amendments on US#1 yields was similar in non-irrigated versus irrigated plots, 6.61 and 7.17 t ha^{-1}, respectively. Rotation crop did not significantly affect US#1 yields. The higher nitrogen rate decreased US#1 yields by 2.13 t ha^{-1}, relative to the lower rate. US#1 yields at the lower N rate were not higher following the green manure rotation crop (31.8 t ha^{-1}) compared to the oat crop (32.8 t ha^{-1}).

The soil amendment and irrigation treatments significantly affected yield during 1995 (Table 1-12). There were no significant interactions between irrigation, soil amendment, and crop rotation. The entire growing season was very dry and supplemental irrigation greatly enhanced crop growth. Irrigation increased yields by 12.43 t ha^{-1} (46%) without amendments and by 10.75 t ha^{-1} (33%) when amendments were applied. Soil amendment treatments increased total yield by 3.36 t ha^{-1} (9%), averaged over all levels of water management, and by 5.49 and 3.81 t ha^{-1} for non-irrigated plots and the optimum level of irrigation, respectively (Figure 1-8). Nitrogen treatments were not included in the 1995 study. Crop rotation effects on yield and US#1 yield were not significant during 1995. Irrigation increased 1995 U.S. #1 yields by 9.74 t ha^{-1} (36%) averaged over all other treatments, by 10.53 t ha^{-1} when no amendments were applied, and by 8.90 t ha^{-1} when amendments were applied (Figure 1-9). Soil amendments increased U.S. #1 yields by 2.69 t ha^{-1} or 8% averaged over treatments. The beneficial effect of soil amendments on US#1 yields was 4.93 t ha^{-1} in non-irrigated versus 3.25 t ha^{-1} for irrigated plots. Early initiation of the irrigation treatments during 1995 may have tempered some of the amendment treatments' beneficial effects on early growth.

The soil amendment treatments used for this study increased soil nutrient concentrations and the uptake of several macro- and micro-nutrients (Porter, unpublished). They also improved soil structure and increased soil moisture content. It is not possible to determine how much of the observed yield response was due to nutrient supply and how much was due to changes in soil physical properties. It is clear from the data that soil amendments and irrigation treatments of this nature cannot substitute 1:1 as inputs for enhancing yields. As was noted above, the amendments tended to enhance early-season plant growth in these studies, while the irrigation effects on growth began at mid-season because treatments began after tuber initiation. During 1993, yields in the non-irrigated, amended treatments were higher than those in the best unamended, irrigation treatment; however, the amended treatments were not able to maintain this advantage during the drier 1994 and 1995 growing seasons (irrigation timing was also more appropriate during these seasons). Yields in the non-irrigated, amended treatments were 92 and

82% those of the unamended, irrigation treatments. In comparison, yields in the non-irrigated, unamended treatments were only 72 and 69% those of the unamended, irrigation treatments. From these data, it appears that the yield enhancing effects of the soil amendment treatments were not able to entirely compensate for the dry conditions experienced during these two years (i.e. increases in the moisture reserves within the soil could not compensate for the long periods without rainfall that were experienced during these years). It is noteworthy that yields were consistently higher for the irrigated/amended treatments than the irrigated/unamended by an average of 7.06 t ha^{-1} or 19%. Only the irrigated and amended treatments consistently reached or exceeded our target yield potential of 40 t ha^{-1} for this experiment, suggesting that the soil structural and nutrient supply improvements provided by the amendments can be beneficial even in irrigated systems.

Even though we detected few significant interactions between the irrigation and soil treatments in these experiments, it is likely that the two types of management have many overlapping and interacting effects that will reveal themselves under specific conditions and growth stages. We had expected to see interactive effects of irrigation and soil management on yield in this study, because both management approaches were expected to affect soil moisture content and plant water status. We were not able to detect these effects on total yield; however, interactive effects of these two inputs were detected on several other variables.

Tuber Quality. Irrigation did not affect tuber size in the 1993 experiment (Table 1-10); however, it did enhance tuber size during the drier 1994 and 1995 growing seasons (Tables 1-11 and 1-12). Maintaining the soil water after tuber initiation allowed tuber bulking to proceed normally and thus increased the percentage of yield greater than 5.7 cm in diameter. This upward shift in tuber size during dry years would enhance the Maine industry's ability to market larger-sized, premium quality consumer packs on a consistent basis without excess loss due to undersized tubers. Soil amendment treatments had little effect on tuber size during 1993 and 1995, but significantly increased tuber size during 1994 (Table 1-10 to 1-12). Rotation crop had no effect on tuber size within these studies.

Essentially no common scab was observed in this study. Incidence of sunburned, misshapen, and growth-cracked tubers was not dramatically influenced by the irrigation, soil amendment, and crop rotation treatments within this study (Tables 1-10 to 1-12). Late blight inoculum was widely present in the area during 1993 and foliar lesions were observed in this experiment several weeks prior to vine desiccation. High September rainfall, combined with high soil moisture from the late-applied supplemental irrigation program resulted in severe tuber decay incidence (Table 1-10) and this field would have been abandoned if it were a commercial field. Over 40% of the yield in the highest irrigation treatment consisted of decayed tubers. Where no irrigation was applied decay incidence averaged 17.2%, well above the incidence needed for the crop to be a disaster in storage (Table 1-10). The soil amendment treatment significantly increased the percent rotten tubers observed during 1993; however, the effect was small relative to the increase caused by the irrigation treatments (Table 1-10). Incidence of tuber rot was low during 1994 and 1995 (Tables 1-11 and 1-12). Irrigation and soil amendment significantly increased rot incidence during 1994

Table 1.9. Effects of irrigation and soil amendments on stomatal resistance and transpiration rate (1994).

Treatments	-----July 20------		-----July 21-----		-----Aug. 4------		-----Aug. 11*-------	
	Stom. Res. (s/cm)	Transp. Rate (ug/cm²/s)	Stom. Res. (s/cm)	Transp. Rate (ug/cm²/s)	Stom. Res. (s/cm)	Transp. Rate (ug/cm²/s)	Stom. Res. (s/cm)	Transp. Rate (ug/cm²/s)
Irrigation level:								
Non-irrigated check	2.42	11.0	1.60	11.8	1.06	17.2	2.87	8.2
Moderate irrigation	1.85	9.4	1.36	12.8	0.74	20.4	1.44	11.4
Soil amendment:								
no amendment (unamended)	2.54	9.0	1.72	11.0	1.01	17.2	2.19	9.8
compost and manure (amended)	1.73	11.4	1.24	13.6	0.79	20.3	2.12	9.9
AOV Results:								
Irrigation	NS	NS	NS	NS	0.09	NS	NS	NS
Soil amendment	NS	NS	0.06	*	0.08	*	NS	NS
Irrigation x Soil amendment	NS	NS	NS	0.07	NS	NS	NS	NS

* data obtained from a series of measurements throughout the day

Table 1.10 Yield, tuber size distribution, US#1 yield, percent external defects, percent rotten tubers and specific gravity of Superior potatoes grown under varying irrigation and soil management treatments in 1993, Aroostook Farm, Presque Isle, Maine.

Treatments	Total Yield t ha^{-1}	Tuber size distribution (%) <2.9	2.9-5.7	5.7-10.2	>10.2	US#1 Yield t ha^{-1}	External Defects %	Decayed Tubers %	Specific Gravity Mg m^{-3}
		------------cm diameter-----------------							
Irrigation									
check	42.7	2	9	86	3	27.7	17.2	17.2	1.077
reduced	43.0	2	8	86	3	24.6	21.0	24.6	1.077
moderate	39.6	2	9	86	2	17.8	20.7	41.3	1.075
Crop rotation									
oats	41.8	2	9	87	2	23.3	19.6	28.5	1.076
green manure	41.8	2	8	86	3	23.5	19.6	26.9	1.076
Amendment									
unamended	37.5	2	9	86	2	21.7	19.6	25.7	1.078
amended	46.1	2	8	86	3	25.0	19.6	29.7	1.075
AOV Results:[1]									
Irrigation (I)	ns	ns	ns	ns	ns	**	ns	**	ns
Rotation (R)	ns	ns	ns	ns	ns	ns	ns	ns	ns
Amendment (A)	**	ns	0.06	ns	0.06	**	ns	*	**
R x A	ns	ns	ns	ns	ns	ns	ns	ns	ns
I x R	ns	ns	ns	ns	ns	ns	*	ns	ns
I x A	ns	ns	ns	ns	ns	ns	ns	ns	ns
I x R x A	ns	ns	ns	ns	ns	ns	ns	ns	ns

[1] Based on analysis of variance, ns=no significant difference; *=significant at 5% level; **=significant at 1% level.

Table 1-11 Yield, tuber size distribution, US#1 yield, percent external defects, percent rotten tubers and specific gravity of Superior potatoes grown under varying irrigation and soil management treatments in 1994, Aroostook Farm, Presque Isle, Maine.

Treatments	Total Yield t ha^{-1}	Tuber size distribution (%) <2.9	2.9-5.7	5.7-10.2	>10.2	US#1 Yield t ha^{-1}	External Defects %	Decayed Tubers %	Specific Gravity Mg m^{-3}
		-----------cm diameter			-------------				
Irrigation									
check	27.9	5	23	72	0	25.9	3.0	0.1	1.072
reduced	35.3	3	17	80	0	32.8	3.6	0.4	1.082
moderate	37.9	3	15	82	0	35.2	3.0	1.1	1.078
Crop rotation									
oats	34.2	4	18	78	0	31.7	3.4	0.5	1.083
green manure	33.2	4	19	78	0	30.8	3.1	0.6	1.084
Amendment									
unamended	29.6	4	21	75	0	27.3	3.8	0.4	1.084
amended	37.7	3	16	80	0	35.2	2.7	0.7	1.083
AOV Results:[1]									
Irrigation (I)	**	0.07	*	*	ns	**	ns	**	**
Rotation (R)	ns	ns	ns	ns	ns	ns	ns	ns	ns
Amendment (A)	**	0.08	**	**	ns	**	*	**	ns
R x A	ns	ns	ns	ns	ns	ns	ns	ns	ns
I x R	ns	ns	ns	ns	ns	ns	ns	*	ns
I x A	ns	ns	ns	ns	ns	ns	ns	**	ns
I x R x A	ns	ns	ns	ns	ns	ns	ns	ns	*

[1] Based on analysis of variance, ns=no significant difference; *=significant at 5% level; **=significant at 1% level.

Table 1-12 Yield, tuber size distribution, US#1 yield, percent external defects, percent rotten tubers and specific gravity of Superior potatoes grown under varying irrigation and soil management treatments in 1995, Aroostook Farm, Presque Isle, Maine.

Treatments	Total Yield t ha^{-1}	Tuber size distribution (%) <2.9	2.9-5.7	5.7-10.2	>10.2	US#1 Yield t ha^{-1}	External Defects %	Decayed Tubers %	Specific Gravity Mg m^{-3}
		-----------cm diameter----------							
Irrigation									
check	30.0	3	15	82	0	28.4	2.6	0.2	1.079
reduced	41.6	2	10	87	0	38.2	5.1	0.8	1.071
moderate	41.0	2	11	87	0	38.0	4.4	1.0	1.071
Crop rotation									
oats	38.3	2	11	86	0	35.6	3.8	0.7	1.074
green manure	36.8	3	13	84	0	34.0	4.3	0.6	1.073
Amendment									
unamended	35.2	2	13	85	0	33.5	4.1	0.3	1.076
amended	39.2	2	11	86	0	36.2	3.9	1.0	1.071
AOV Results									
Irrigation (I)	**	ns	*	*	ns	**	ns	ns	*
Rotation (R)	ns	ns	ns	ns	ns	ns	ns	ns	ns
Amendment (A)	**	0.06	ns	ns	ns	*	ns	*	**
R x A	ns	ns	ns	ns	ns	ns	ns	ns	ns
I x R	ns	ns	ns	ns	ns	ns	*	ns	ns
I x A	ns	ns	ns	ns	ns	ns	ns	ns	ns
I x R x A	ns	ns	ns	ns	ns	ns	ns	ns	ns

[1] Based on analysis of variance, ns=no significant difference; *=significant at 5% level; **=significant at 1% level.

and there was a significant irrigation x amendment interaction. Amendment increased rot incidence only at the highest level of irrigation (data not shown). Soil amendment also slightly increased rot incidence during 1995 (Table 1-12) and most of this rot occurred within the irrigated plots (data not shown). Previously, we presented data indicating that the soil amendment resulted in higher soil moisture content and that this effect was particularly pronounced under irrigation. It is possible that the higher soil moisture levels predispose the tubers to decay. We have no data indicating whether the amendments contained plant pathogens at the time that they are spread onto the soil.

The hollow heart incidence of large tubers was generally low within these three experiments (data not presented). The treatments had only minor effects on hollow heart incidence during 1993 and 1995. Hollow heart was more prevalent during 1994 and irrigation significantly increased hollow heart incidence (data not presented). Soil amendment treatments did not significantly increase hollow heart incidence in any of the studies.

The amendment treatment significantly reduced tuber specific gravity during 1993 and 1995, but had no effect during 1994 (Tables 1-10 to 1-12). The effect on gravity was relatively small during 1993. Irrigation significantly reduced specific gravity during 1994 and 1995, but not during 1993. The effects were quite large during 1994 and 1995. Specific gravity in the non-irrigated check plots was unusually high for Superior during 1994, due to the very low August rainfall. The decline in specific gravity caused by irrigation brought the specific gravity down to levels which are fairly normal for Superior. During all four years, the lowest specific gravities were typically detected in the plots receiving both soil amendments and the highest rate of irrigation. Specific gravity was depressed by the combined effect of available moisture (during years that were generally dry through August) and the availability of excess nutrients from the amendments. Surprisingly, the nitrogen and crop rotation treatments had no significant effects on specific gravity within this series of experiments. Nitrogen supply was apparently not an important determinant of specific gravity on this site.

Small-scale storage samples were washed and screened for the incidence of surface diseases and defects on a weight basis during 1994. Primarily, the samples were graded for incidence of black scurf, scab, silver scurf, black dot, and enlarged lenticels. Incidence of black scurf was significantly increased by irrigation during 1994 (data not presented). No other significant effects on tuber surface defects were observed.

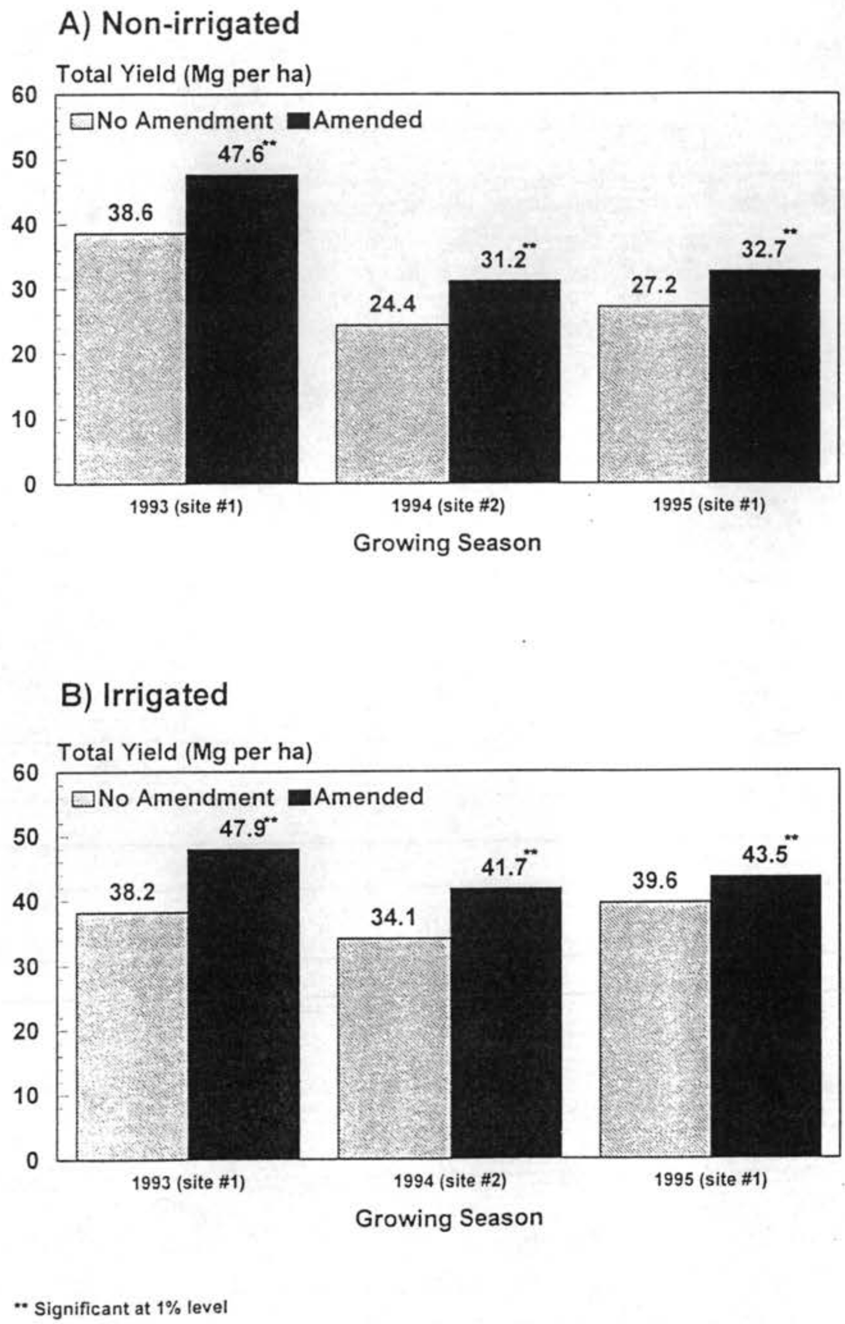


Figure 1-8 Total yield response of Superior potatoes to soil amendment application, 1993-95. A) Response in the non-irrigated plots; B) Response at the "best" level of irrigation. NS, *, and ** indicate nonsignificant effects and significant effects at $p<0.05$ and 0.01, respectively.

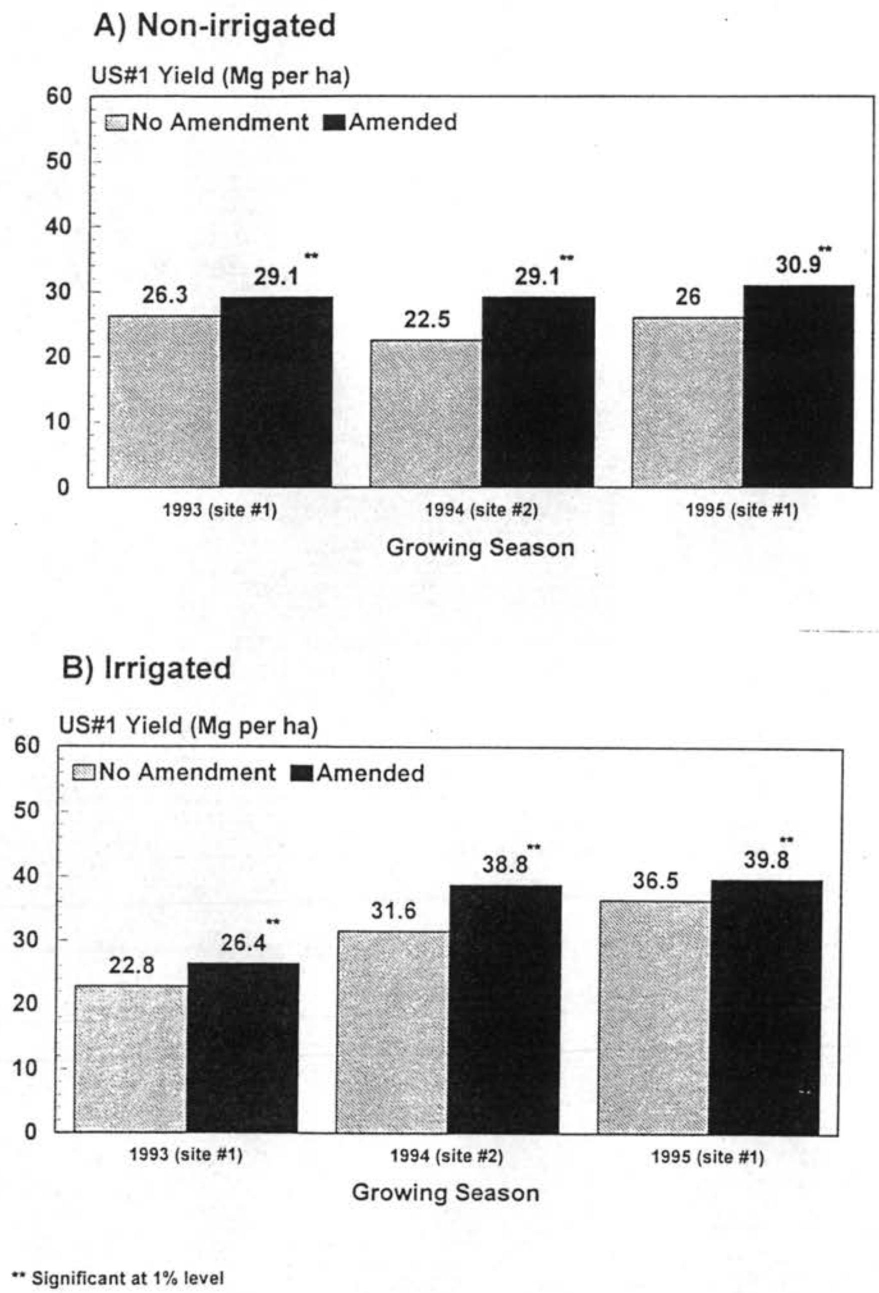


Figure 1-9 US#1 yield response of Superior potatoes to soil amendment application, 1993-95. A) Response in the non-irrigated plots; B) Response at the "best" level of irrigation. NS, *, and ** indicate nonsignificant effects and significant effects at $p<0.05$ and 0.01, respectively.

Partial Budgets. The economic results take the form of partial budgets. The main idea behind partial budgeting is to estimate the change in profitability resulting from a change in the farming operation, for example a change in input use, production practice or equipment investment. It is based on the profit maximization result that if an action returns more in additional benefits than it costs, then total profit will increase. If not, then total profit will decrease and the action should not be taken. The additional benefits can include both increased revenues and reduced costs, while the additional costs can include both higher costs and lower revenues. Partial budgeting accounts for these components of a contemplated change in a systematic manner. This method of analysis is preferable to total profitability estimation when results are to be used directly by producers, since it does not include such farm-specific ownership factors such as land values or basic machinery and equipment complements that are not expected to change with the contemplated action. Therefore, the partial budgeting results are applicable to a broader range of farm situations than are total profitability results (Boehlje and Eidman, 1984).

The results of a partial budgeting exercise indicate the profitability of an assumed change *relative to* the profitability of the scenario representing the current situation. In the case of the field experiments conducted in this study, two separate assumptions about the current situation should be made so that a complete picture of the possible options is available for decision making.

The first of these is that the producer is faced with the decision to irrigate or to apply soil amendments as a water management strategy, assuming he/she has not yet invested in irrigation equipment or developed a water source and has not yet invested in spreading equipment (we assume disking equipment is part of the basic machinery complement). In this case, the two options are compared to the dryland, no amendment situation. In other words, the hypothesis being tested is whether or not *either* irrigation *or* soil amendment is a profitable option in a conventional potato production system.

The second scenario of interest is the case where the producer has made the irrigation investment decision and is faced with the decision to apply soil amendments *in addition to* reduced amounts of supplemental irrigation or to use moderate irrigation alone. The current situation in this case is the moderate irrigation, no amendment treatment, and the hypothesis to be tested is whether or not soil amendment is a profitable *complement* to irrigation in the conventional potato production system.

Care has been taken to make the input prices and field operations costs used in the analysis reflect prevailing commercial conditions in Aroostook County, Maine at the time period of the study. A potato price of \$6.60 cwt^{-1}. is assumed for comparison purposes. Input prices and field operation costs are taken from Marra (1996). Annualized manure spreader ownership costs per acre are taken from Estes, et al. (1996). Costs associated with water source development (a holding pond) and irrigation equipment (pipe, pumps and center pivot systems) are adapted from Marra and Woods (1990). The Index of Prices Paid by Farmers, 1990-1992=100 (USDA) was used to adjust all prices to reflect 1995 values. All comparisons are made on a per-acre basis, assuming a 400-acre farm with 200 acres in potato production each year. Prices used in the analysis are listed in Table 1-13.

Table 1-13. Prices assumed in the economic analysis

Item	*Unit*	*Price*
Potato selling price	$/cwt	$ 6.60
Potato waste compost, delivered (Price 1)	$/ton	$ 18.18
Beef manure, delivered (Price 1)	$/ton	$ 6.21
Spreading cost, variable	$/acre	$ 17.90
Irrigation water application	$/acre-inch	$ 10.92
Spreader ownership costs	$/acre/year	$ 5.14
Irrigation system ownership costs[a]	$/acre/year	$163.35

[a] Includes 1 large and 1 small center pivot, holding pond development, pumps, pipe and land preparation costs for irrigating 200 acres.

In some cases, however, no local market prices are available. For example, the prices paid for compost and manure do not represent market prices because a market has not yet developed in this area. If there were a developed market, the prices for these amendments should fall, since at present there is only one supplier for these inputs in the area. As more suppliers enter the market, competitive forces would cause the prices to be bid down. Therefore, the comparisons are constructed first using the actual prices paid for these inputs (Price 1) and then, again, assuming market prices 35% lower than the current prices (Price 2).

Partial budgeting results for the three comparisons discussed above are shown in Tables 1-14, 1-15 and 1-16. Each budget is based on the simple average of the 1994 and 1995 experimental results only, since the irrigation system was not set up in time in 1993 to provide full-season irrigation. Yield responses were averaged over the two years and over the two rotation sub-treatments, since differences between the rotation crops were not significantly different. Moderate irrigation alone resulted in an additional 94.75cwt per acre and additional profit of about $250 acre^{-1} (Table 1-14). Amendment alone provided an additional 52cwt per acre, but was not profitable (Table 1-15). Amendment with reduced irrigation yielded an additional 34.75 cwt A^{-1} compared to moderate irrigation without amendment, but this also was not a profitable option (Table 1-16).

Table 1-14. Partial budget: Dryland, no amendment *vs.* moderate irrigation, no amendment

Increased Revenue				
	Additional Marketable Yield x Potato Price		94.75cwt x $6.60	625.35
Reduced Costs				0
	None			
Total Additional Benefits				**625.35**
Decreased Revenue				
	None			
Increased Costs				
	Irrigation Water Application	Cost/acre-inch x inches applied	(10.92 x 6)	65.52
	Annualized Irrigation Ownership Costs			163.35
Total Additional Costs				**228.87**
NET ADDITION TO PROFIT				***396.48***

Breakeven Analysis. In the two cases where amendment is added, it is illustrative to perform a breakeven analysis to see what potato prices or amendment costs would have to be for the option to break even from a profitability standpoint. This analysis is shown in Table 1-17. First, amendment costs are held constant at each of the two price assumptions (Price 1 and Price 2, which is 65% of Price 1 for each amendment), and the breakeven potato price is calculated. Then potato price is held constant to calculate what the average price of the amendments would have to be to break even.

When amendment prices are assumed to be those actually paid for them during the research project, the potato price would have to be more than $13 cwt^{-1}. for amendment to pay for itself in terms of the value of additional potato production achieved. This potato price is too high to be reasonably expected in Maine. However, under the Price 2 assumption about amendment prices (65% of the prices actually paid), the breakeven potato price for the addition of amendments is within the reasonable range for Maine seed producers. Thus, soil amendment may be a profitable option for these producers. Breakeven potato prices for the moderate irrigation, no amendment *vs.* reduced irrigation, amendment scenario are not reasonably achievable regardless of the amendment price assumption.

The breakeven average amendment price (assuming a $6.60 cwt^{-1} potato price) is between 20 and 30 percent of the average actual amendment price paid per ton. Although unlikely in the near future, it may be possible to achieve these prices eventually with a well-developed amendment market in the area.

Table 1-15. Partial Budget: Dryland, no amendment *vs.* dryland, amendment

Increased Revenue				Price 1	Price 2
	Additional Marketale Yield x $6.60/cwt	52 X 6.60	$343.20		
Reduced Costs					
	None		$0.00		
Total Additional Benefits				**$343.20**	**$343.20**
Decreased Revenue					
	None				
Increased Costs					
	Annualized Spreader Ownership			$5.14	$5.14
	Annual Spreader Operating Costs			$17.90	$17.90
	Potato Waste Compost			$399.96	$260.04
	Beef Manure			$273.24	$177.76
	Disk Operating Costs (2 times)			$13.44	$13.44
Total Additional Costs				**$709.68**	**$474.28**
NET ADDITION TO PROFIT				($366.48)	($200.84)

Table 1-16. Partial Budget: Moderate irrigation, no amendment *vs.* reduced irrigation, amendment

			Price 1	Price 2
Increased Revenue				
Additional Marketable Yield x $6.60/cwt	34.75 x 6.60	$229.35		
Reduced Costs				
Irrigation Water Application	2.5" x 10.92	27.3		
Total Additional Benefits			256.65	256.65
Decreased Revenue				
None				
Increased Costs				
Annualized Spreader Ownership			5.14	5.14
Annual Spreader Operating Costs			17.9	17.9
Potato Waste Compost			399.96	260.04
Beef Manure			273.24	177.76
Disk Operating Costs (2 times)			13.44	13.44
Total Additional Costs			709.68	474.28
NET ADDITION TO PROFIT			**-453.03**	**-217.63**

Table 1-17. Breakeven analysis

Scenario	**Breakeven Potato Price ($/cwt)**		**Breakeven Average Amendment Price ($/ton)**
	Amendment Prices Assumed		
	Price 1	*Price 2*	
Dryland, no amendment *vs.* dryland, amendment (Table 1-15)	$ 13.65	$ 9.13	$ 3.39
Moderate irrigation, no amendment *vs.* reduced irrigation, amendment (Table 1-16)	$ 20.42	$ 13.66	$ 2.49

Summary--Objective #1. An experiment conducted at Aroostook Research Farm, Presque Isle, ME from 1993 to 1995 examined the effects of soil management practices as an alternative to supplemental irrigation for enhancing yield of potatoes (cv. 'Superior'). Soil management treatments compared soil amendment (unamended vs. soil amended annually with 44 t ha^{-1} manure and 10 t ha^{-1} compost) and crop rotation practices (1:1 rotation with oats versus 1:1 rotation with green manure). Amendments were initially applied during 1992. Non-irrigated production was compared with two rates of supplemental irrigation. Supplemental irrigation began after tuber initiation and was scheduled based on gypsum blocks buried 23 and 46 cm below the surface of the potato row.

The soil amendment treatment increased soil organic matter content, cation exchange capacity, and the soil test levels of potassium, calcium, magnesium, and zinc. It also decreased soil bulk density and increased water stable aggregate content of the soil. Gravimetric moisture sampling revealed that the amendment program increased soil moisture levels throughout much of the growing season by about 10% and that plots receiving both soil amendment treatment and supplemental irrigation had particularly high soil moisture content. We were not able to detect any effects of the soil amendment treatments on water infiltration rates or moisture retention characteristics. The green manure crop rotation increased inorganic nitrogen levels within the soil, but had no other significant effects on soil properties.

The soil amendment treatments enhanced early growth of the potato crop and increased the size of the plant canopy. Amendments significantly increased total yields in all three years of the study (8.62, 8.18, and 3.36 t ha^{-1}, respectively). US#1 yields were also increased (3.25, 7.84, and 2.69 t ha^{-1}, respectively). Irrigation increased yields by 3.14, 7.84, and 12.1 t ha^{-1} over the three respective years. The rotation crop treatments did not significantly affect yields or US#1 yields. There were no significant interactions among irrigation, rotation crop, or soil amendment treatments.

During 1993, total yields in the non-irrigated, amended treatments were higher than those in the best unamended, irrigation treatment; however, the amended treatments were not able to maintain this advantage during the drier 1994 and 1995 growing seasons. Yields in the non-irrigated, amended treatments were 92 and 82% those of the unamended, irrigated treatments. In comparison, yields in the non-irrigated, unamended treatments were only 72 and 69% those of the unamended, irrigation treatments. From this, it appears that the yield enhancing effects of the soil amendment treatments make them attractive alternatives to supplemental irrigation; however, the soil amendment program was not able to entirely compensate for the dry conditions experienced during 1994 and 1995. It is noteworthy that yields were consistently higher for the irrigated/amended than the irrigated/unamended treatments by an average of 7.06 t ha^{-1} or 19%. Only the irrigated/ amended treatments consistently reached or exceeded our target yield potential of 41 t ha^{-1}, suggesting that the soil structural and nutrient supply improvements provided by the amendments can be beneficial even in irrigated systems. It is not possible to determine how much of the response was due to nutrient supply and how much was due to changes in soil physical properties.

Irrigation increased tuber size during two of the three study years, while the soil amendment treatment increased tuber size only during 1994. There were no treatment effects on incidence of sunburned, misshapen and growth-cracked tubers. Supplemental irrigation dramatically increased the incidence of tuber rot during 1993 and slightly increased rot incidence during 1994. Soil amendment also tended to increase the incidence of tuber rot, possibly because it results in increased soil moisture levels throughout much of the growing season. Soil amendment did not dramatically affect the incidence of hollow heart in these experiments, but it decreased specific gravity in two of three growing seasons. Crop rotation did not generally affect tuber quality in this study.

Based on the experimental results reported in this study, it appears that supplemental irrigation alone may be a profitable investment for producers of Superior potatoes regardless of market outlet. It is important to note that both of the growing seasons represented within the present study (1994 and 1995) were relatively dry and, therefore, that the yield response to irrigation was relatively large.

With current (and reasonably foreseeable) prices for compost and beef manure, amendment alone and amendment coupled with reduced irrigation are not profitable options for Maine potato producers, according to the results obtained in this study. However, only a few years of data may not tell the whole story when it comes to adoption of a technology that could provide increasing, future benefits. The current soil amendment system was designed to rapidly build soil organic matter and was not designed to optimize the rate of amendment application. It is likely that amendment rates and frequencies of application were much higher than were necessary for obtaining the yield increases observed in this work. In this experiment, we did not lower fertilizer rates to compensate for the nutrients present in the amendments. Other experiments have clearly indicated that fertilizer cost savings (65% N, 50% P_2O_5, and 70% K_2O) can be achieved when these amendments are utilized. Also, it is extremely likely that the positive effects of the amendments on soil properties and crop yields will last for several seasons after amendment applications have ceased. The potential of soil amendments should be studied over a much longer time period before any conclusions are drawn as to their true feasibility for Maine producers. Potential impacts on plant diseases and tuber decay should also receive more attention.

A2. Detailed Findings and Accomplishments by Objectives (Objective 2)

Introduction. An interdisciplinary study of the potato agroecosystem was initiated at the University of Maine in 1991 with the objective of developing an understanding of the ecology of the ecosystem, and based on this, develop a sustainable potato production system in northern Maine. The focus of the research has been to investigate: a) nutrient and water dynamics, b) pests and natural enemy dynamics, and c) the subsequent impacts of these factors on crop growth, yields, and economic performance. This work is being done in the context of a long-term ecosystem study and short-term component studies. In the long-term study we are contrasting three pest management strategies, two potato varieties, and two soil fertility management programs in 96 large plots (0.06 ha each). For the pest management programs, all potato plots are sampled once per week and decisions to apply foliar insecticides are based on estimated pest densities. The pest management treatments being compared include: 1) conventional (CONV), which relies on synthetic insecticides and economic thresholds recommended by the Maine Cooperative Extension Service; 2) reduced input (RI), which relies on the same materials as the CONV, but the thresholds for pests are doubled; and 3) biological (BIO), which relies on biological and bio-rational materials for pest suppression, again, based on recommended economic thresholds.

In 1992, the combination of *Bacillus thurengiensis (Bt)* and *Beauveria bassiana* (applied as a tank mix) for larvae, and rotenone for adults were utilized for CPB control in the BIO system. Based on sampled densities compared to the thresholds, BIO plots were treated an average of 1.25 times with *Bt/Beauveria* plus 0.75 times with rotenone while CONV plots received 2.25 applications of Asana®, and RI plots required 1.25 applications of Asana®. Seasonal densities of small larvae were higher in the BIO plots than in CONV, but no differences were observed in large larval densities. June was very cool during 1992 and the the average residence time for eggs in the field was 14 days. Predators which target the egg stage may add significantly to a biological management program for CPB in relatively cool environments such as northern Maine.

In 1993 and 1994, studies were conducted to evaluate augmentative releases of *Perillus bioculatus* in the Potato Ecosystem Study. This research consisted of 1) a small-plot experiments in which releases of the predator were assessed alone and in combination with other biological management tactics, and 2) a large system level study in which *P. bioculatus* was used as one component of the BIO pest management program which was compared to CONV and RI programs. All *P. bioculatus* were produced at the USDA-ARS Laboratory in Yakima, WA, and shipped as nymphs to Maine for release.

Small Plot Tests: ***Evaluation of Augmentative Releases of P. bioculatus in Combination with Bt and B. bassiana.***

Methods:

In 1993, a study was conducted at the University of Maine Potato Research Farm in Presque Isle, ME, to examine the impact of releases of the predators, *P. bioculatus* and *C. maculata*, and foliar applications of the insect pathogens, *Beauveria bassiana* and *Bacillus thurengiensis (Bt)*, on the survival of the Colorado potato beetle (CPB). Three blocks each containing eight 7.5 x 7.5 m plots of potatoes were planted in early June, and the 10 to 25 m areas between plots were seeded with barley. Two 1.8 x 3.7 x 1.2 m cages were set over the two northern rows in each plot. Because of the low densities of CPB naturally colonizing the plots, 19 adult CPB per plot were released outside the cages from July 7-12. Five adults (4 females, 1 male) and 20 egg masses were released into each cage on July 17, 1993. The following treatments were randomly assigned to each of the eight plots per block: 1) *Bt* alone, 2) *B. bassiana* alone, 3) *P. bioculatus* alone, 4) *Bt* and *B. bassiana*, 5) *Bt* and *P. bioculatus*, 6) *B. bassiana* and *P. bioculatus*, 7) *Bt*, *B. bassiana*, and *P. bioculatus*, and 8) control with no releases or applications. The two cages within each plot received the same treatments as the uncaged portion of the plot, and *C. maculata* releases were randomly assigned to one of the two cages, with the other acting as a control (no *C. maculata* release). Foliar applications and predator releases were initiated with the establishment of sufficient CPB egg populations in mid July. *Bt* and *B. bassiana* treatments (rates = 2.3 l Foil® ha^{-1}, and 5 x 10^{13} conidia ha^{-1} in 2% oil formulation (Mycotech Bioproducts, Inc.) respectively) were applied to both the caged and uncaged portions of the plots with a CO_2 back-pack sprayer on July 18-22, July 28-29, and August 5-6. *P. bioculatus* nymphs were released at densities of 1 per plant outside the cages on each of three dates: July 20, August 3, and August 12, and densities of 1 per plant, 0.625 per plant, and 1 per plant on each of these dates inside the cages. *C. maculata* adults[1] were released at densities of 10 per cage (0.5 per plant) in the designated cages. CPB life stages and predator densities were sampled weekly on 15 plants per plot (outside cages) from July 21 - August 23. Emergence of CPB adults in the cages was monitored every other day from August 25 - September 16.

In 1994, the previous year's study was replicated with the following modifications at the University of Maine's Aroostook Farm Potato Research Center in Presque Isle, ME, plus the University of Maine Sustainable Agriculture Research Farm in Old Town, ME. This second site is in central Maine, and usually experiences earlier and greater densities of colonizing CPB than the northern Maine site in Presque Isle. Potatoes were planted in Presque Isle on June 4. Weekly applications of copper hydroxide (Kocide®, 1.7 kg/ha) were applied to all plots beginning July 8, to protect against late blight. Foliar treatments were applied on four consecutive weeks (July 8, July 14, July 21, and July 28), and three *P. bioculatus* releases were made on July 6, July 12 and July 20. *B. bassiana* treatments were applied at the same rate of conidia mixed in a 0.01% Silwet® solution. *C. maculata* were not released in 1994, however, one 1.8 x 3.7 x 1.2 m cage was placed in each plot on August 4, to monitor emergence of CPB adults. Thirty-two 7.5 x 7.5 m plots of potato were planted at the University of Maine Sustainable Agriculture Research Farm in Old Town, Maine, on May 21, 1994. Twenty-four plots were utilized to replicate the treatments applied at the Presque Isle site. Plots were treated once with glyphosate (4.7 l/ha) prior to plant emergence to control weeds, and received two applications of copper hydroxide (Kocide®, 1.7 kg/ha) in late July. *P. bioculatus* were released twice on June 22 and July 6 at the rate of 2 nymphs per plant (2nd and 3rd instars). Foliar applications of *Bt* and *B. bassiana* were made at four weekly intervals beginning June 27, 1994. On July 19, four 0.074 m^2 circular emergence cages were randomly set under the potato canopy in each plot to monitor the emergence of summer adults. Cages were sampled three times per week.

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[1] *C. maculata* adults were provided by Dr. Don Vacek at the USDA APHIS Biological Control Laboratory in Mission, TX.

The remaining 8 plots in Old Town were utilized to conduct the following two additional experiments: 1) a comparison of full rate of *Bt* (2.3 l ha^{-1}) with ½ rate *Bt* (1.15 l ha^{-1}), both with and with*out P. bioculatus*, and 2) a comparison of four sprays of *B. bassiana* applied at weekly intervals over 4 weeks, with four sprays of *B. bassiana* applied over 2 weeks with 48 hrs between applications one and two, and application three and four. Treatment application, plot maintenance, and sampling were conducted as described above.

In 1994, 15 randomly selected larvae per plot were collected 36 hours post spray in each of the plots receiving *Bt* or *B. bassiana* treatments, and the control. Larvae were held individually in petri dishes in the laboratory at ambient temperatures for 12-14 days. Larvae were fed fresh foliage every other day, and monitored daily for death and sporulation. Also, in 1994, visual assessments of percent defoliation were made on 15 plants per plot on July 25 at the Old Town site, and August 8 at the Presque Isle site.

Analyses:

Three-way repeated measure analyses of variance (ANOVAs) were performed to test for *Bt, B. bassiana,* and *P. bioculatus* effects on the densities of CPB adults, egg masses, and each of the four instar larvae throughout the growing season. In addition, one-way repeated measures ANOVAs were conducted to compare the effectiveness of each combination of biological agents with one another and the control. In 1993, a four-way nested ANOVA was performed to test for *Bt, B. bassiana, P. bioculatus,* and *C. maculata* (nested factor) effects on total adult emergence in the field cages. In 1994, three-way and four-way ANOVAs were conducted to test for treatment effects on emergence of summer adults, and defoliation.

For the *Bt* rate and *B. bassiana* application strategy experiments conducted at Old Town in 1994, similar analyses were performed. Two-way repeated measures ANOVA was performed to test for *Bt* rate and *P. bioculatus* effects on densities of CPB lifestages throughout the season, and one-way repeated measures ANOVAs were conducted to compare the effectiveness of each combination of these treatments with each other. One-way repeated measures ANOVAs were used to test for *B. bassiana* application strategy effects on CPB lifestages at the same site in 1994. For both experiments, two- and one-way ANOVAs were used to test for treatment effects on adult emergence and percent defoliation.

Results:

Data analyses of the 1993 CPB population densities outside the cages indicate that there were significantly fewer CPB adults in the *Bt* treatments ($F_{1,14}$=10.9, p=0.005), and significantly more adults in the *B. bassiana* treatments ($F_{1,14}$=7.3, p=0.02) than the remaining treatments. However, there were no treatment effects on egg mass or first instar larval densities, and no interactions between treatments. Densities of CPB second and third instar larvae were reduced by the *Bt* treatments ($F_{1,14}$=22.5, p=0.0003, and $F_{1,14}$=49.28, p=0.0001, respectively), but no other significant differences were observed between *B. bassiana* or *P. bioculatus* treatments and the control. Significant reductions in fourth instar densities were seen in all treatments over the control, with densities lowest in the *Bt* plots (0.05 $plant^{-1}$), and lower in the *B. bassiana* plots (1.26 $plant^{-1}$) than in the *P. bioculatus* plots (1.38 $plant^{-1}$). There were no significant interactions between any of the natural enemy treatments.

When data were analyzed using one-way ANOVAs with each combination of agents considered a treatment, densities of second and third instar larvae were significantly lower than the check in all combinations with *Bt* (Figure 2-1). Third instar densities were lower than the check in the *P. bioculatus* treatment. Fourth instar densities were significantly lower in all treatments compared to the check, and combinations with *Bt* were lower than those without *Bt.*

Analysis of the 1993 cage data revealed no impact of *C. maculata* releases on total emergence of adult CPB; however, *Bt*, *B. bassiana*, and *P. bioculatus* significantly reduced the number of emerging adults. The lowest mean emergence was observed in plots with all three mortality agents, however, only *P. bioculatus* alone resulted in significantly higher adult emergence than the remaining non-control treatments (Figure 2-2). There were no differences in the densities of emerging adults between *Bt* treatments and *B. bassiana* treatments. These results indicate that considerable additional mortality occurred during the pupal stage in the soil in the *B. bassiana* treatments.

The 1994 results of the small plot study at both sites were similar to the 1993 results; however, several treatment effects were detected earlier in the population than during the previous year. There were no significant treatment effects on CPB adult densities, but egg mass densities were significantly reduced in the *Bt* plots at the Presque Isle site ($p=0.001$). *P. bioculatus* effects were detected in small larval densities at the Old Town site ($p=0.02$), with a mean of 1.67 ± 0.48 first instars in the predator plots over the season, versus 4.26 ± 1.11 in the non-predator plots. Predators significantly reduced densities of second, third, and fourth instars in Presque Isle, whereas in 1993, *P. bioculatus* effects were not detected until the fourth instar stage. *Bt* effects were also detected in second ($p=0.03$) and third ($p=0.01$) instar densities in Old Town, and all instars at the Presque Isle site. In all cases, densities of CPB larvae were lower in all *Bt* plots versus non-*Bt* plots. *B. bassiana* treatments significantly reduced fourth instar densities in Presque Isle, but not at the Old Town site.

Interactions between treatments were detected for only egg mass densities at the Presque Isle site. *Bt* treatments without predators appeared to have little effect on egg mass densities at this site, however, *Bt* in combination with *P. bioculatus* resulted in fewer egg masses than *P. bioculatus* applied by itself. *B. bassiana* resulted in fewer egg masses than the control; however, *B. bassiana* with predators resulted in more egg masses than treatments with predators and no *B. bassiana.* These differences in egg mass densities were greatest during the third and fourth week after treatment when overall egg mass densities in the study had declined considerably, so their significance on the overall population pressure is minimal.

When comparing each combination of biological agents as separate treatments (using one-way ANOVAs), significant treatment effects on CPB were not seen in adult, egg mass or small larval densities at either site, but were seen in large larval populations. At the Presque Isle site, all treatments with the exception of *B. bassiana* alone resulted in lower third instar densities than the control (Figure 2-3). In addition, *Bt* with *P. bioculatus* and the combination of all three agents resulted in lower densities of third instars than *P. bioculatus* alone. All treatments had significantly lower densities of fourth instars than the control, but *Bt* alone and all combined treatments resulted in lower fourth instars than *P. bioculatus* alone and *B. bassiana* alone. At Old Town, densities of third instars were greater in the *B. bassiana* alone treatment than all other non-control treatments, and only *B. bassiana* and *Bt* combined resulted in densities significantly below the control (Figure 2-4). At the same site, *Bt* in combination with *P. bioculatus* and the combination of three agents resulted in the lowest mean density of fourth instars, but the high variability between plots made treatment differences difficult to detect. Again, fourth instar densities at this site were higher in the *B. bassiana* alone treatment than the *Bt* with *P. bioculatus*, and the combination of three agents.

Emergence of summer adults at both sites was significantly impacted by all biological agents, and emergence in all treatments was lower than in the control (Figure 2-5). There were no significant differences between the treatments receiving some form of CPB control, but the lowest mean emergence at the Presque Isle site was observed with the combination of three agents. In addition, 42% of the adults emerging in *B. bassiana* treatments at the Old Town site died within 10 days of emergence, whereas, only 15% of those in non-*B. bassiana* plots died over the same period. However, there was no difference in post-emergent mortality of adults at the Presque Isle site. There was a significant *B. bassiana* effect on the number of collected larvae that died post spray at both sites (p=0.04 and 0.0001 for Old Town and Presque Isle, respectively), but there was no effect of *Bt* (p=0.44) in Old Town, and no interaction between *B. bassiana* and *Bt* at either site (p=0.09 and 0.23 for Old Town and Presque Isle, respectively). In Old Town, 61% of those collected from *B. bassiana* plots died compared with 42% from *Bt*, 44% from the *B.bassiana* + *Bt*, and 21% of the control. In Presque Isle, 90% of those collected from *B. bassiana* plots died compared with 53% from *Bt*, 95% from the *B.bassiana* + *Bt*, and 19% of the control. There were also significant *B.bassiana* (p=0.001 and 0.0001 for Old Town and Presque Isle, respectively) effects on the sporulation of those larvae that did die post spray, but no interactions at either site (p=0.97 and 0.56 for Old Town and Presque Isle, respectively). In Old Town, 41% of those dying from *B. bassiana* treatments sporulated compared with 53% from the *B. bassiana* + *Bt*, 4% from the *Bt* treatment, and 41% from the control. In Presque Isle, 61% of those dying from *B. bassiana* treatments sporulated compared with 67% from the *B. bassiana* + *Bt*, 2% from the *Bt* treatment, and 0% from the control.

Defoliation ratings ranged from 0.3% for plots with the combination of all three biological control agents at both sites to 54.3% and 27.6% in the controls in Old Town and Presque Isle, respectively (Figure 2-6). Defoliation ratings in all biological treatments were significantly less than the control, but not different from each other in Old Town. However, the *B. bassiana* alone treatment did result in more defoliation than the other treatments in Presque Isle. In Old Town, the *B. bassiana* plots did not have significant reductions in CPB larval densities, but resulted in only 6.2% defoliation. Large larvae were observed on the foliage, but most were infected and caused little feeding damage.

Comparisons of half and full rates of Bt with and without *P. bioculatus*, did not result in any significant differences in densities of CPB lifestages between treatments. However, mean densities of large larvae were consistently lower in the *Bt* + *P. bioculatus* plots compared with the other treatments, with no difference between the full rate with *P. bioculatus* and the half rate with *P. bioculatus* . Emergence of summer adults was significantly greater in the control plots than all other treatments, but half rate *Bt* did not differ from the full rate of *Bt*. Again, percent defoliation was low in all of the treatments and was significantly less than that observed in the controls.

Comparisons of consecutive applications of *B. bassiana* compared with applications applied at weekly intervals showed no significant differences between treatments in the densities of

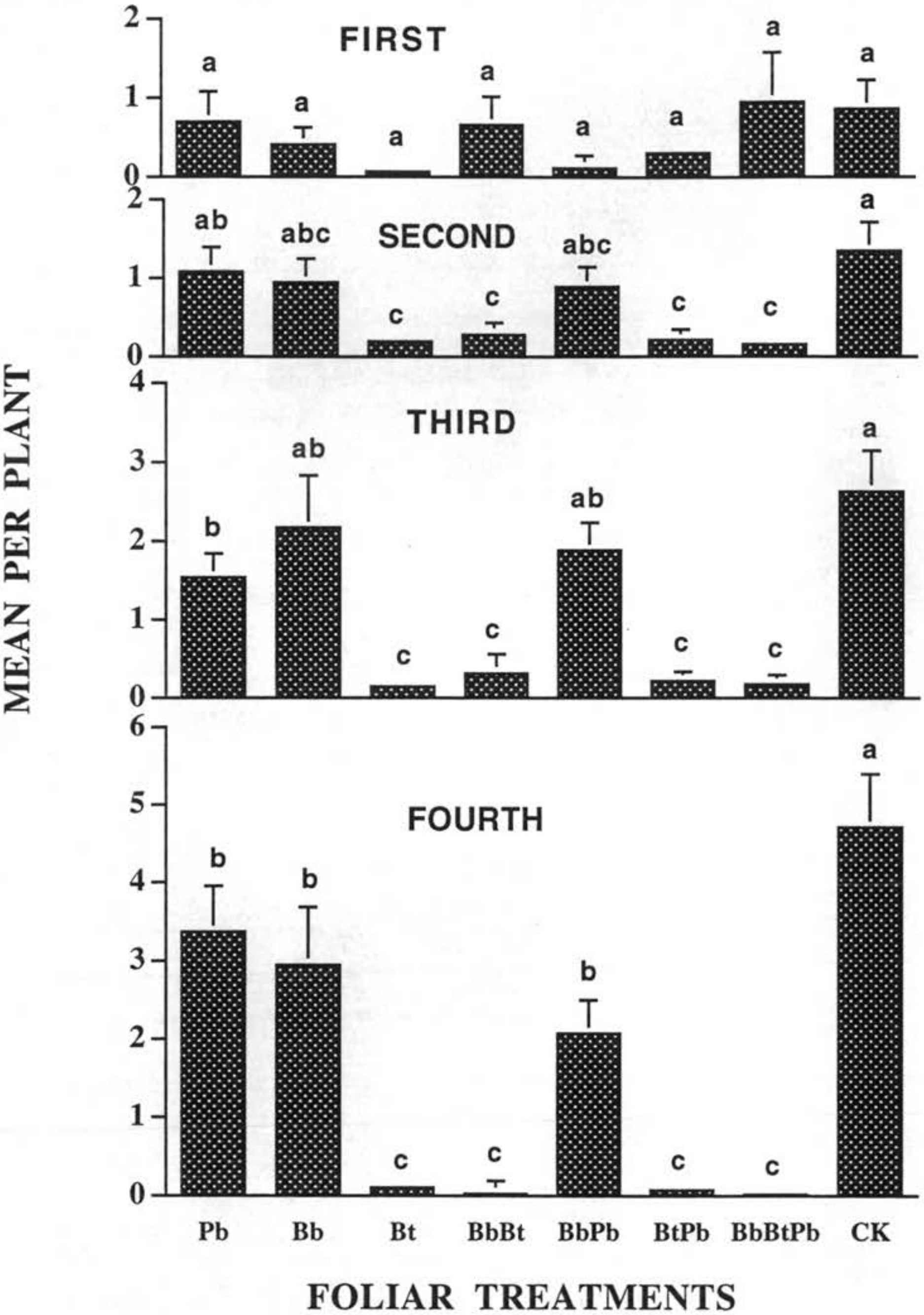

Figure 2-1. CPB larval densities in the biological control experiment in Presque Isle, ME, 1993. Pb = *Perillus bioculatus,* Bb = *Beauveria bassiana,* and Bt = *Bacillus thurengiensis.* Bars represent the mean ± SE density over the season. Bars with the same letter are not significantly different at the p=0.05 (Fisher's LSD).

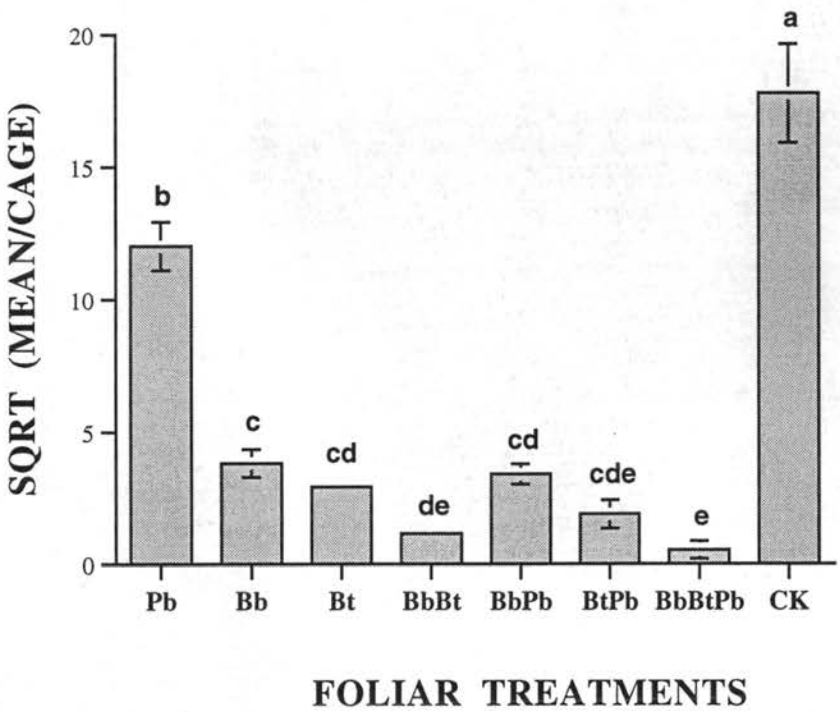

Figure 2-2. Emergence of CPB adults in cages in biological control experiment in Presque Isle, ME, 1993. Pb=*P. bioculatus,* Bb=*B. bassiana,* Bt=*B. thuringiensis.* Bars represent the mean±SE of three cages. Bars with the same letters are not significantly different at $p<0.05$ (Fisher's LSD).

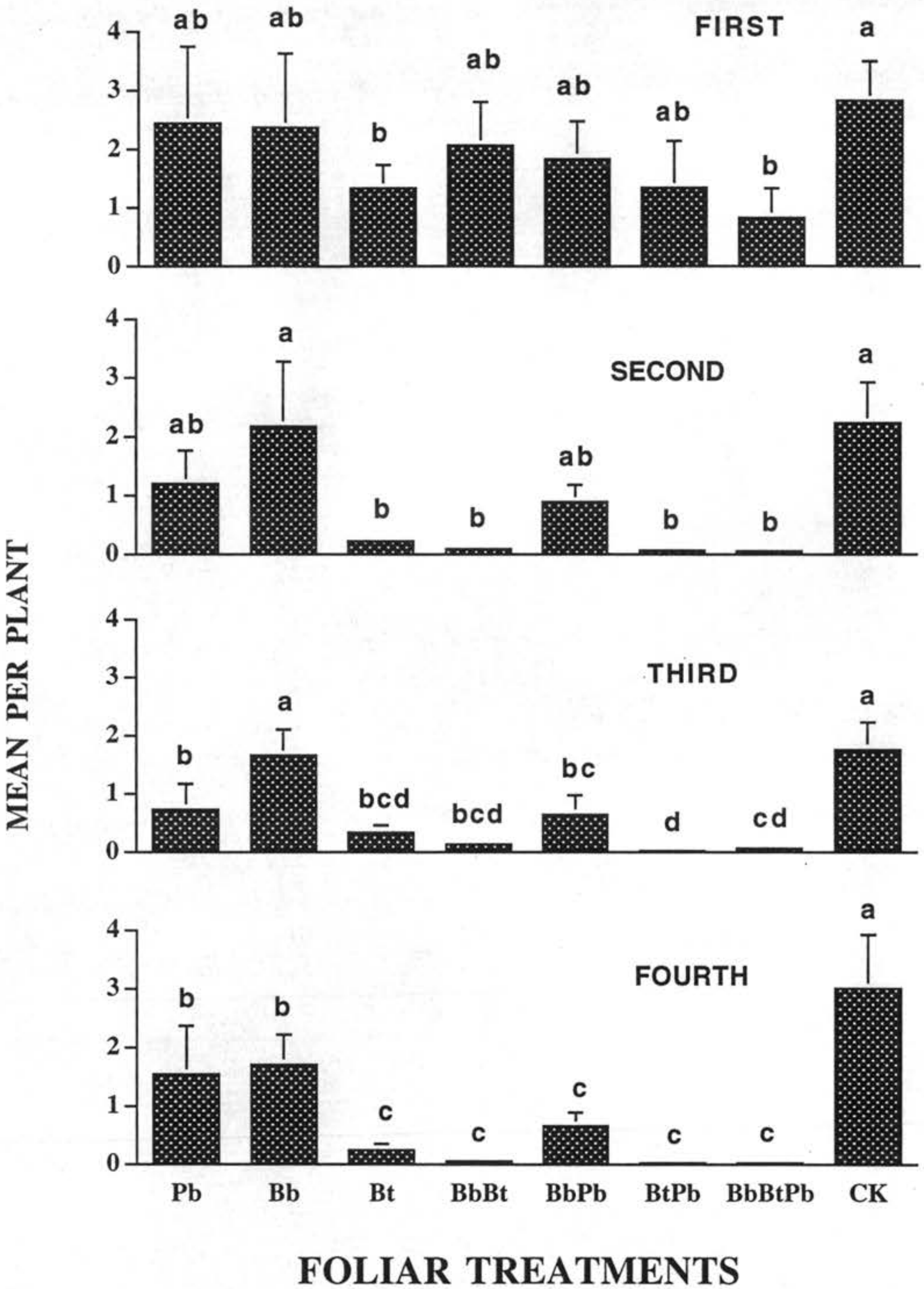

Figure 2-3. CPB larval densities in biological control experiment in Presque Isle, ME, 1994. Pb = *Perillus bioculatus,* Bb = *Beauveria bassiana,* and Bt = *Bacillus thurengiensis.* Bars represent the mean ± SE density over the season. Bars with the same letter are not significantly different at the p=0.05 (Fisher's LSD)

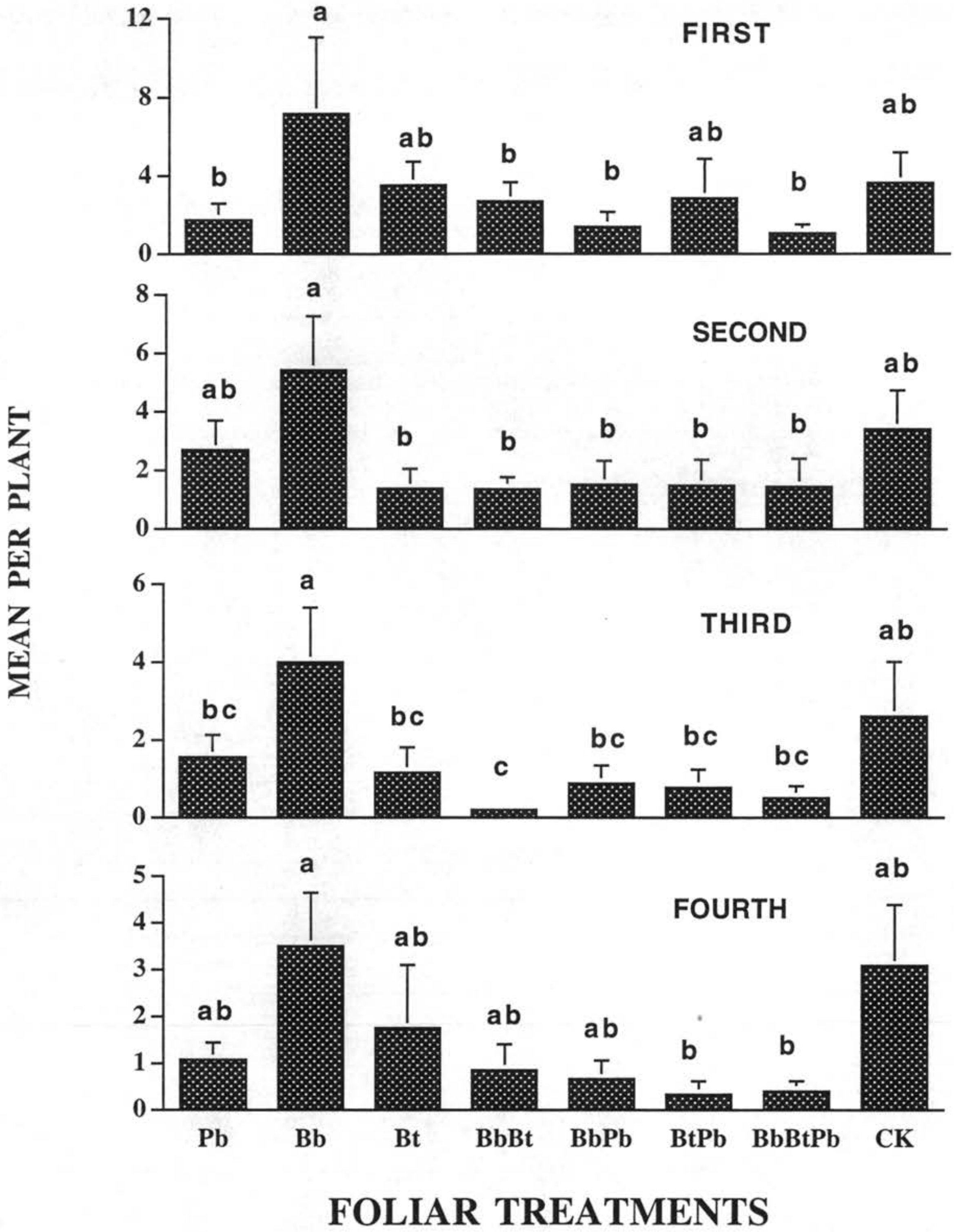

Figure 2-4. CPB larval densities in biological control experiment in Old Town, ME, 1994. Pb = *Perillus bioculatus,* Bb = *Beauveria bassiana*, and Bt = *Bacillus thurengiensis.* Bars represent the mean ± SE density over the season. Bars with the same letter are not significantly different at the p=0.05 (Fisher's LSD)

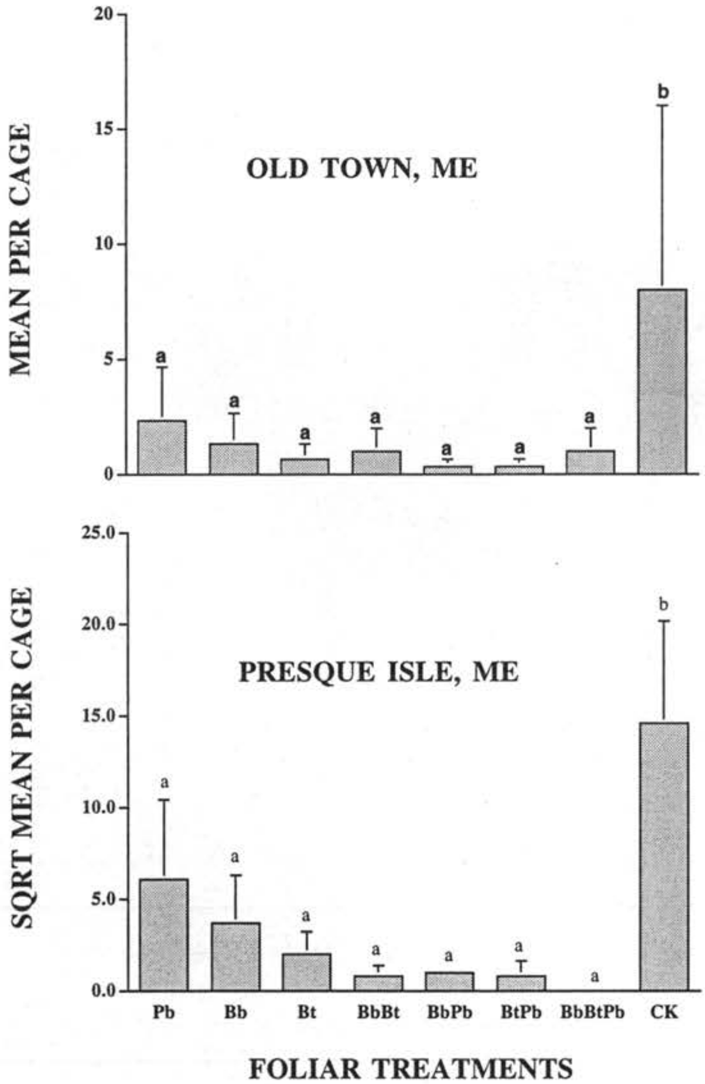

Figure 2-5. Emergence of CPB adults in field cages in the biological control experiments in Old Town and Presque Isle, ME, 1994. Pb = *Perilllus bioculatus,* Bb = *Beauveria bassiana,* and Bt = *Bacilllus thurengiensis.* Bars with the same letters are not significantly different at the $p<0.05$ (Fisher's LSD) at that site.

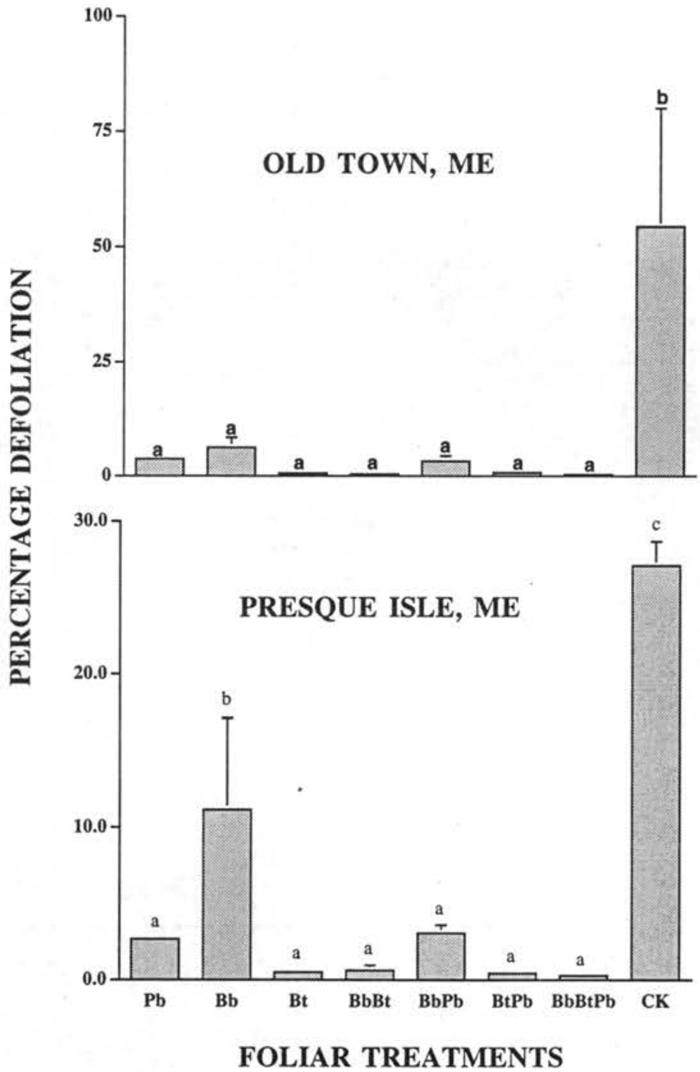

Figure 2-6. Percent defoliation of potato plants in biological control experiments in Old Town and Presque Isle, ME, 1994. Pb = *Perillus bioculatus,* Bb = *Beauveria bassiana,* and Bt = *Bacillus thurengiensis.* Bars with the same letters are not significantly different from each other at that site.

immature life stages of the CPB. Although high variation resulted in no significant differences between treatments and control for summer adult emergence and defoliation, the trends in the means showed lower emergence and defoliation in the *B. bassiana* treatments than the controls, but no difference between application strategies. Emergence averaged 8.0 $\pm$ 3.5 for controls versus 1.3 + 0.9 for weekly *B. bassiana* applications, and 2.0 + 1.5 for consecutive *B. bassiana* applications. Defoliation averaged 54.3 $\pm$ 25.7% for controls versus 6.2 + 2.2% for weekly *B. bassiana* applications, and 4.3 + 0.8% for consecutive *B. bassiana* applications.)

Systems Study. ***A System Level Comparison of Pest Management Programs*****.**

Methods:
In both 1993 and 1994, the combination of CPB biological control agents (*P. bioculatus, Bt,* and *B. bassiana)* was used as part of an integrated biological management strategy for pests in an on-going Potato Ecosystem study at the University of Maine Aroostook Farm Potato Center in Presque Isle, Maine. This BIO pest management program was compared with RI and CONV programs. Each pest management strategy was applied to four 0.05 ha plots per block and replicated in four blocks, making a total of 0.78 ha treated per management strategy. *P. bioculatus* releases were initiated in the BIO plots with the onset of CPB oviposition. Nymphs were released at a density of one per plant on three occasions between July 20 and August 12 in 1993, and July 6 and 20 in 1994 . CPB life stages were sampled on 50 to 30 plants per plot each week throughout the growing season. Applications of foliar insecticides (microbial and chemical) were made when average CPB densities within a block exceeded action thresholds. Action thresholds for CPB in the different treatments were as follows: a.) biological treatment - 0.5 adults, 1.5 small larvae, or 1.5 large larvae, b.) reduced input - 1.0 adults, 8.0 small larvae, or 3.0 large larvae, and c.) conventional - 0.5 adults, 4.0 small larvae, or 1.5 large larvae. Seasonal densities of eggs, small larvae, and large larvae and incidence of adults were calculated and compared between pest management treatments using ANOVAs.

Results:
In 1993, CPB densities exceeded the threshold an average of three times during the growing season in CONV, once in RI, and once in BIO. As a result, the CONV plots received three treatments with Asana® (0.7 l ha^{-1} for each treatment), the RI plots received one application of Asana® (0.7 l ha^{-1}), and the BIO plots received one application of *Bt* and *B. bassiana* in combination (5 x 10^{13} *B. bassiana* conidia ha^{-1} and 11.7 l *Bt* ha^{-1}).

The incidence of CPB adults was significantly lower in BIO than RI (Figure 2-7), and the seasonal densities of eggs, small and large larvae were all lower in BIO than CONV and RI (Figure 2-8). As might be expected given the higher thresholds, there were more small and large larvae in RI than in CONV, indicating that all of these strategies successfully reduced CPB populations below economic thresholds. There were no significant differences in yields between pest management treatments.

In 1994, CPB densities exceeded thresholds an average of three times in CONV, twice in RI, and 2.75 times in BIO. The CONV and RI plots were again treated with Asana® (0.7 l/ha). The BIO plots received two applications of *Bt* and *B. bassiana* (5 x 10^{13} *B. bassiana*

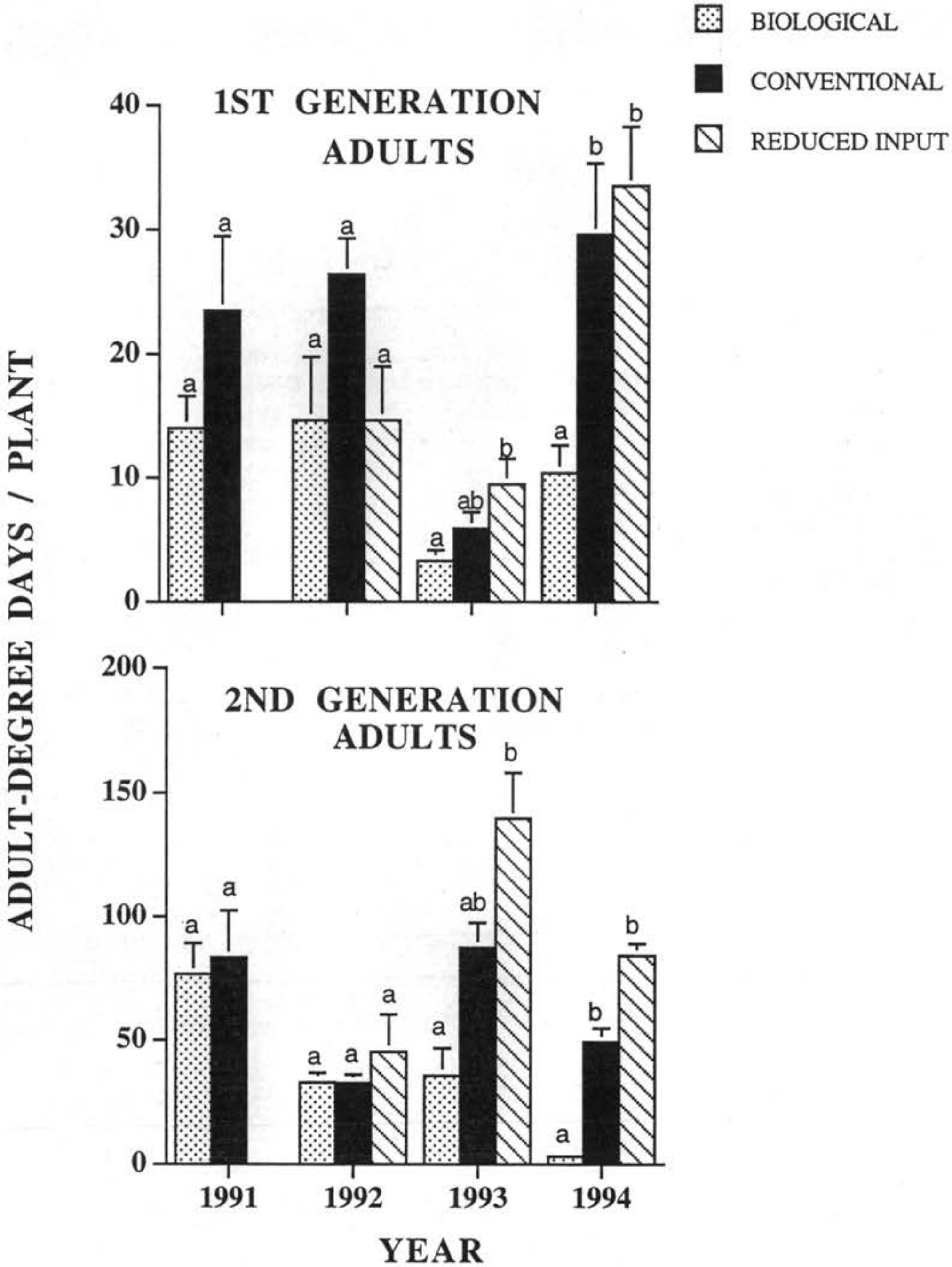

Figure 2-7. The incidence of first (overwintered) and second (summer) generation CPB adults in the different pest management treatments in the Potato Ecosystem Study in Presque Isle, ME,1991-1994. Columns with the same letter indicate no significant differences between treatments within that year.

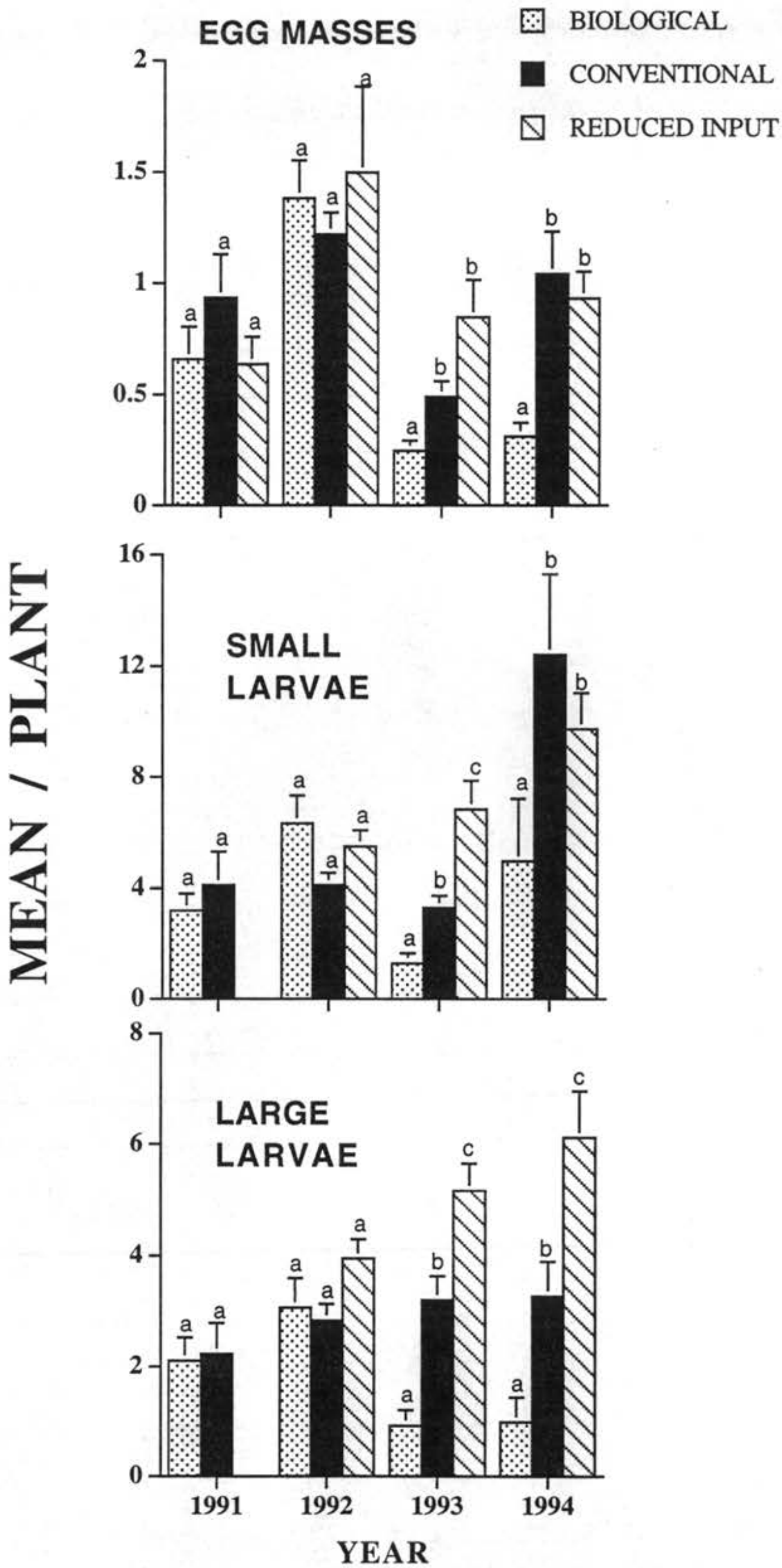

Figure 2-8. The seasonal densities CPB eggmasses and small and large larvae in the different pest management treatments in the Potato Ecosystem Study in Presque Isle, ME,1991-1994. Columns with the same letter indicate no significant differences between treatments within that year.

conidia/ha and 11.7 l *Bt/* ha) for larvae, and three out of four blocks were treated with rotenone (Rotacide® 5EC, 6.1 l/ha) for summer adults.

In 1994, densities of all CPB lifestages (first generation adults, egg masses, small and large larvae, and summer adults, Figures 7-8) were significantly lower in BIO compared with both RI and CONV. In this on-going study, CPB populations have been declining in the BIO relative to the other treatments since 1992. The proportion of adults in the plots prior to the applications of any foliar treatments or predator releases has been lower in the BIO plots compared with the other treatments (Figure 2-9).

Cooperating Farms. In 1996, attempts were made to implement the biological management program for the Colorado potato beetle on two commercial farms: Wood Prairie Farm in Bridgewater, ME, and Gorenson Farm in Dresden Mills, ME. Wood Prairie Farm is a certified organic farm in northern Maine, owned and operated by Jim and Megan Gerritson. Gorenson Farm is a mixed vegetable farm in central Maine, owned and operated by Rob Johanson and Jan Gorenson.

At Wood Prairie Farm, a 9.25 acre field of potatoes was divided into 6 sections for comparing different combinations of foliar formulations of *Bt* (Novodor 3%® provided by Abbott Laboratories, Chicago, IL), and *Beauveria bassiana* (Mycotrol®, provided by Mycotech Bioproducts, Butte, MT), with and without releases of the predatory stinkbugs, *Perillus bioculatus*. The planned foliar treatments included: full rate (3 qt/A) of *Bt* alone, full rate of *Bt* with *B. bassiana*, and ½ rate *Bt* (1.5 qt/A) with *B. bassiana*. The entire field was flamed on June 20 for weed and CPB control. Three releases of stinkbug predators (provided by the USDA-APHIS Biological Control Center, Mission, TX) were made at a rate of one nymph per plant on June 26, July 3, and July 10. During and after this time, densities of CPB adults, eggs, and larvae were sampled each week. Densities in all sections (with and without predators) never reached levels requiring foliar applications. Over the season there were no significant differences in CPB densities between sections with and without releases of the predators, although there was a trend for both fewer small and large larvae in areas where the predators were released (Figure 2-10).

At Gorenson Farm, two fields of potatoes (ca. 2 and 7 acres each) were divided into two sections. One section received foliar applications of *Bt* and the other section received foliar applications of *Bt* with *B. bassiana*. No predators were available for release at this site. CPB densities were sampled weekly from June 17 through August 14. Four foliar applications were made on all sections between June 25 and July 22. The application materials and rates were as follows:

Application	Date	*Bt* Treatment[1]	*Bt* + *B. bassiana* Trt.[2]
1	June 25, 28	Raven™ (3 qt/A)	Mycotrol® WP (1 lb/A) + Raven™ (1.5 qt/A)
2	July 6	Raven™ (3 qt/A)	Mycotrol® WP (1 lb/A) + Raven™ (1.5 qt/A)

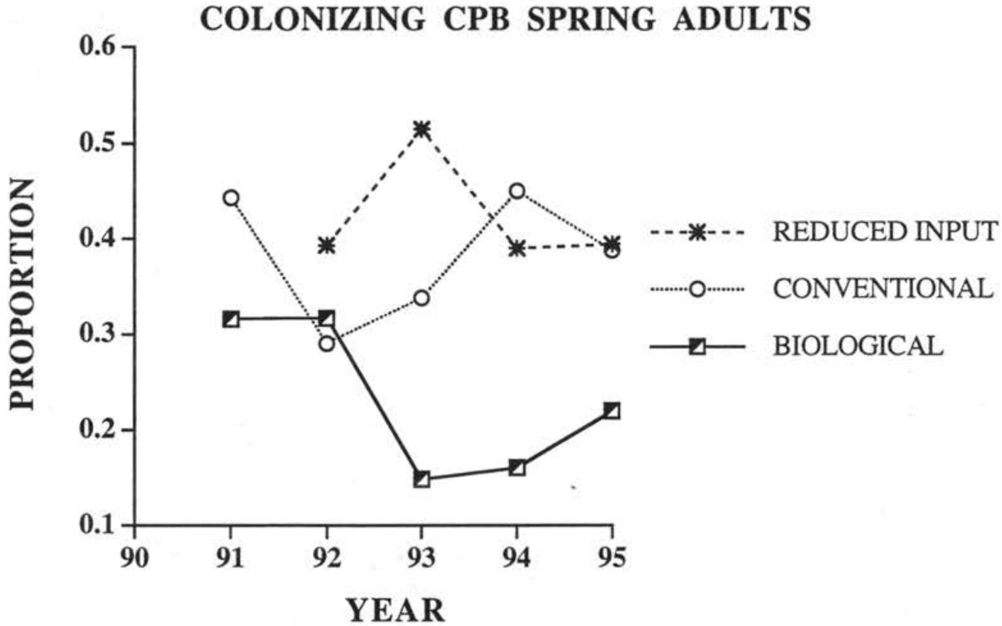

Figure 2-9. The proportion of colonizing (prespray) CPB adults in the different pest management treatments in the Potato Ecosystme Project in Presque Isle, ME, 1991-1995.

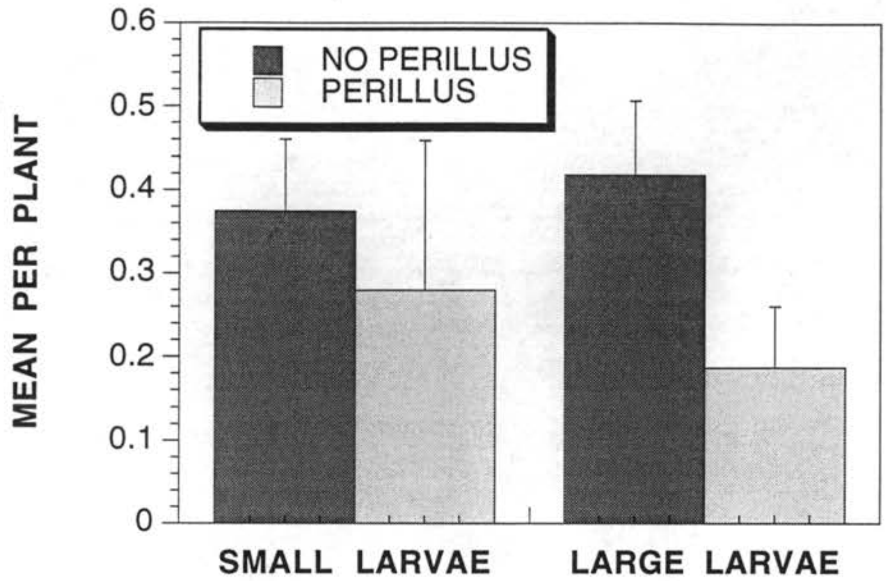

Figure 2-10 . Densities of Colorado potato beetle larvae in plots with and without releases of stinkbug *(Perillus bioculatus)* predators at Wood Prairie Farm in Bridgewater, ME, in 1996.

3	July 12	Novador® (3 qt/A) + Foil® (1 qt/A)	Mycotrol® WP (1 lb/A) + Novador® (3 qt/A) + Foil® (1 qt/A)
4	July 22	Novador® (3 qt/A) + Foil® (1 qt/A)	Mycotrol® ES (1 qt/A) + Novador® (3 qt/A) + Foil® (1 qt/A)

[1] Raven™ provided by Ecogen, Langhorne, PA.
[2] Mycotrol® provided by Mycotech Bioproducts, Inc., Butte, MT.

In field #1 at Gorenson Farm, relative densities of CPB larvae were higher in the *Bt* plus *B. bassiana* treatment section than the *Bt* alone section. However, in field #2, the opposite was true (Figure 2-11). In field #1, the section treated with *Bt* alone was planted and harvested early (starting in mid-July), and there was considerable migration of larvae from this area to the adjacent section which was treated with *Bt* plus *B. bassiana*. This may account for the higher densities of larvae in this section of field #1.

The summer of 1996 was a very good year for potato production, as adequate rainfall resulted in abundant top growth. Both growers were pleased with the resulting yields in all treatments, and did not consider that they had experienced any loss due to CPB populations even when some defoliation was evident. CPB populations will be monitored at the Gorenson farm in 1997 to see if there is any evidence of a carry-over effect from the *B. bassiana* applications as was observed in the systems study at Aroostook Research Farm in Presque Isle.

Objective 2. Economic Results. Table 2-1 contains the yield, total revenue and revenue less Colorado Potato Beetle (CPB) control costs for each treatment/year combination in the study. Revenue less CPB costs were calculated with and without the costs of the *Perillus bioculatus* releases, since this agent was found to be expensive and because any suitable population reductions may be achieved without it. Overall, the reduced input and conventional pest management systems are shown to be economically comparable when revenue minus CPB control costs are considered. The biological management system still does not provide enough protection at a sufficiently reasonable cost to be feasible from the producer standpoint. It does, however, result in less environmental damage than the other two systems and, if the value of those damages are considered, the biological pest management system would compare more favorably with the others. It is beyond the scope of this study to quantify the value of the environmental effects.

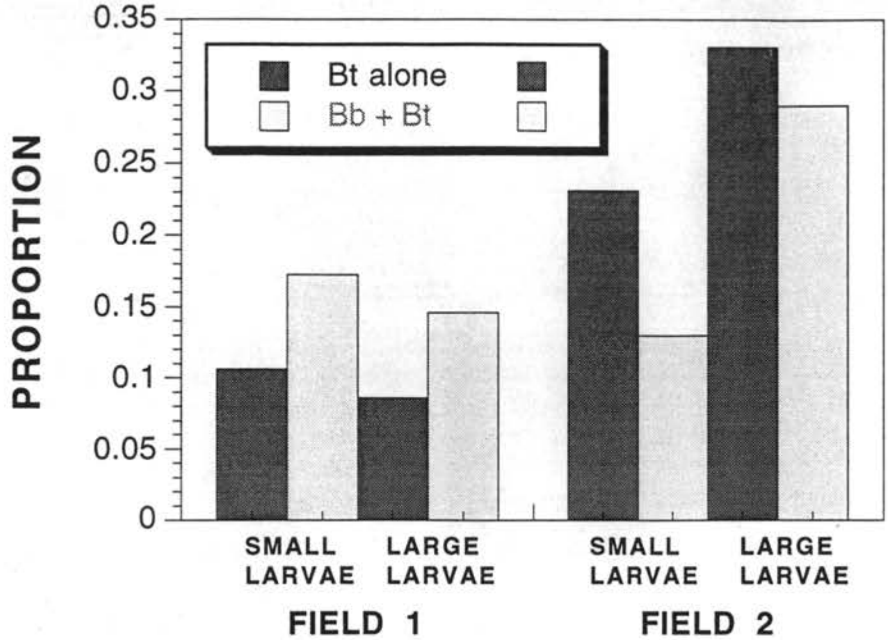

Figure 2-11. Relative densities of Colorado potato beetle small and large larvae at plots treated with either *Bt* or *Bt* plus *Beauveria bassiana*, at Gorenson Farm in Dredens Mills, ME, in 1996. Because egg masses densities varied significantly between sections, densities of larvae are presented relative to egg densities.

Table 2-1. Economic Results for Objective 2

Year	Treatment	Yield (cwt/ac)	Revenue ($/ac)	Revenue less CPB Control Costs ($/ac)
1995	Conventional	190.02	1254.16	1188.24
	Reduced Input	185.78	1226.13	1173.02
	Biological	151.77	1001.71	773.63
	Biological less Perillus Costs	151.77	1001.71	801.63
1994	Conventional	269.68	1779.86	1728.70
	Reduced Input	268.48	1771.96	1737.85
	Biological	194.47	1283.50	1057.50
	Biological less Perillus Costs	194.47	1283.50	1085.50
1993	Conventional	260.95	1722.28	1690.08
	Reduced Input	253.98	1676.25	1657.11
	Biological	250.05	1650.30	1605.84
	Overall Averages:	**Conventional**	**Reduced Input**	**Biological**
	Revenue Less CPB Control Costs	**$1535.67/ac**	**$1530.60/ac**	**$899.83/ac**

Summary -- Objective #2. This study has demonstrated that the Colorado potato beetle can be successfully managed with the combination of biological agents which include releases of the predator, *Perillus bioculatus,* and foliar applications of the pathogens, *Bacillus thurengiensis,* and *Beauveria bassiana.* The combination of all three agents results in greater season-long reduction in CPB populations than any one agent alone. This biological management program was more successful in reducing beetle populations than a conventional insecticide based management program, and a reduced input management program. In addition, the biological management program appears to have carry-over effects between years which is not seen in the other two programs. It is hypothesized that residual levels of *B. bassiana* in the soil and CPB population, may be responsible for reduced adult populations in the spring following treatment. This carry-over effect could greatly enhance the economic viability of biological control programs for this pest.

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