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LEGUME-POTATO ROTATIONS: NITROGEN MANAGEMENT, ECONOMICS, AND PATHOGENS

By

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ABSTRACT

LEGUME-POTATO ROTATIONS: NITROGEN MANAGEMENT, ECONOMICS AND PATHOGENS

By

Timothy Scott Griffin

The implementation of crop rotations in potato production requires additional information on the potential agronomic benefits and the economic viability of rotational systems. The objectives of this research were: (*i*) to quantify legume nitrogen (N) accumulation in the first year of rotations; (*ii*) to evaluate the vine and tuber response of the subsequent potato crop to legume and fertilizer N; (*iii*) to compare net income and income variability of alfalfa- and corn-potato rotations and continuous potato using Monte Carlo simulations; and (*iv*) to evaluate the effect of first year rotation crop and second year N rate on potato pathogen populations and tuber quality parameters.

Potato fertilized with 0 to 225 kg N ha^{-1} was grown following; alfalfa, birdsfoot trefoil, red clover, sweetclover, hairy vetch, corn, fallow and potato, at the MSU Montcalm Research Farm and the Kellogg Biological Station (KBS), respectively. Seeding year harvest of alfalfa, birdsfoot trefoil and red clover generally did not significantly reduce legume N accumulation, compared to a green manure crop of the same species. The subsequent potato crop exhibited a vegetative response to both legume and fertilizer N sources at both locations. Tuber yield was unaffected by rotation or N rate at KBS. At Montcalm, tuber yield increased with N rate following red clover, corn, fallow, and potato. The lack of N response following

the remaining legumes is attributed to a soil moisture deficit induced by spring regrowth of legumes.

Root-lesion nematode populations increased under growing legumes crops in Year 1 (1987) of the rotations, but soil populations in May, 1988, were similar for all rotations. Similarly, soil inoculum levels of *Verticillium dahliae* were unaffected by rotations crop. Potato scab decreased with N rate in 1988, but black scurf and growth cracking increased with N rate.

Using state average yields and costs, continuous potatoes had a higher mean net income, with greater variability, than alfalfa- or corn-potato rotations. A 15% reduction in continuous potato yield resulted in net income being nearly identical to that from the alfalfa hay-potato rotation, but with 37% more variability in net income. The implementation of potato rotations depends most strongly on the assumption of declining potato yield in monoculture.

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PREFACE

Chapters One and Three of this dissertation are written in the style required for publication in the *Agronomy Journal.* Chapter Two, written in English rather than metric units, is in the style required for publication in the *Journal of Production Agriculture.*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

RESPONSE OF POTATO TO LEGUME AND FERTILIZER NITROGEN SOURCES

ABSTRACT

The production of potato (*Solanum tuberosum* L.) in rotation with nitrogen (N)-fixing legumes requires additional information on the N contribution from legumes and on the management of potato N fertilization following legumes. The objectives of this research were to: (*i*) quantify N accumulation by green manure and hay crop legumes in Year 1 of a 2-yr rotation; (*ii*) determine the effect of legume species and management on the vine and tuber yield of the subsequent potato crop grown without N fertilizer; and (*iii*) evaluate the N fertilizer response of potato following legumes, corn (*Zea mays* L.), fallow, and potato. Rotations were established at two Michigan locations in 1987; the Montcalm Research Farm at Entrican and the Kellogg Biological Station (KBS) at Hickory Corners. Soil types were McBride sandy loam (coarse-loamy, mixed, frigid, Alfic Fragiothods) at Montcalm and Oshtemo sandy loam (coarse-loamy, mixed, mesic, Typic Hapludalfs) at KBS. First year crops included: 'Saranac' alfalfa (*Medicago sativa* L.), 'Viking' birdsfoot trefoil (*Lotus corniculatus* L.), and 'Michigan Mammoth' red clover (*Trifolium pratense* L.) as green manure (0 harvests) and hay crops (2 to 3 seeding year harvests); non-dormant 'Nitro' alfalfa (KBS only) as hay; sweetclover (*Melilotus* spp.) and hairy vetch (*Vicia villosa* Roth) green manure; 'Pioneer 3737' corn; fallow; and potato ('Shepody' at Montcalm, 'Atlantic' at KBS). Potato (Shepody) fertilized with 0, 75, 150, or 225 kg N ha^{-1} was grown in Year 2 (1988). Alfalfa and red clover dry matter

yield was similar at Montcalm (6.2 and 5.7 Mg ha^{-1}, respectively), but 'Saranac' alfalfa yielded more than 'Nitro' alfalfa and red clover at KBS. Seeding year harvest of alfalfa, birdsfoot trefoil and red clover did not reduce plowdown N yield [PDN=fall(herbage+root)N + spring herbage N] compared to a green manure crop of the same species, except for a 28% reduction for red clover at Montcalm. Periodic harvesting also reduced weed competition with alfalfa and red clover. Tuber yield (without N fertilizer) of the subsequent potato crop was not affected by rotation at either location. However, late season vine N content was 93 (Montcalm) and 111% (KBS) higher following legumes than following non-legumes and was significantly correlated with the PDN yield of the preceding legume. This indicated that N mineralized from legume material was available for vegetative growth late in the season, but may not have been available during tuber initiation to affect tuber yield. Tuber yield did not respond to N rate in any rotation at KBS, attributed to a soil moisture deficit (even with irrigation) during the first half of the growing season. At Montcalm, tuber yield was not affected by N rate following alfalfa, birdsfoot trefoil, sweetclover and hairy vetch, with an average yield of 30.9 Mg ha^{-1}. Based on this mean yield, these legumes replaced 69 kg N ha^{-1}, compared to the response in the corn-potato rotation. Total tuber yield increased linearly with N rate following fallow and potato at Montcalm; following corn and red clover, maximum tuber yield required 150 kg N ha^{-1}.

INTRODUCTION

Many crops, including potato, have been shown to benefit from crop rotation, due to both nitrogen (N) and non-N effects. Although recent research on producing agronomic crops like corn in rotation has focused on the N contribution from a preceding legume crop (Adams et al., 1970; Hesterman et al., 1986; Bruulsema and Christie, 1987; Harris and Hesterman, 1990), research on potato rotations has focused primarily on non-N effects, including pathogen or disease control (Curl, 1963; Brodie et al., 1969) and improvement of soil physical properties (Odland and Sheehan, 1957; Saloman, 1962). Little information is available on the potential for supplying all or a portion of the potato N requirement, or on the management of potato N fertilization, when an N-fixing legume is included in a short-term rotation with potato. An accurate quantification of the N contribution from different legume species, and the effect of harvest management strategy (ie. green manure versus hay crops) on this contribution, is needed to more efficiently manage N fertilizer in legume-potato rotations. Nitrogen management is particularly important in legume-potato rotations because potatoes often require high rates of N (from 175 to 448 kg N ha^{-1}) to maximize marketable tuber yield (Dubetz and Bole, 1975; O'Sullivan, 1978), yet are adversely affected by insufficient or excess soil N during the growing season. Low levels of soil N early in the growing season reduce the number of tuber initiates (Roberts et al., 1982), while high soil N levels delay tuber initiation and promote excessive vine growth (Kleinkopf et al., 1981; Lauer, 1986; Ojala et al., 1990), thereby reducing tuber yield and increasing the proportion of immature tubers.

Total N accumulated by legumes during the seeding year, from both biological fixation and uptake from soil, is affected by legume species and harvest management. Nitrogen content at plowdown can vary widely among legume green manure species, with previous estimates ranging from 9 (sweetclover; Sprague, 1939) to 357 kg N ha^{-1} (red clover; Groya and Sheaffer, 1985). Recent estimates of N accumulation by alfalfa and red clover green manure, the forage legumes most widely used in rotations in the northern U.S. and southern Canada, have generally been between 125 and 225 kg N ha^{-1} (Groya and Sheaffer, 1985; Bruulsema and Christie, 1987). The effect of harvest frequency and timing on N accumulation by these two legume species has been variable, depending in part on the weed control methods used. Stickler and Johnson (1959) used no herbicides and found that alfalfa and red clover contained more N when clipped once or twice during the seeding year than if they were unharvested, attributed to a reduction in weed competition from periodic clipping. Groya and Sheaffer (1985) used triflualin (α,α,α-trifluoro-2,6-dinitro-*N*,*N*-dipropl-ρ-toluidine) to control weed competition in seeding year alfalfa and red clover. They found that harvesting once during summer (herbage regrowth, roots, and crowns incorporated in the fall) or during both summer and fall (only roots and crowns incorporated in the fall) reduced the amount of N in alfalfa and red clover at plowdown by 20-70%, compared to green manure crops. Total N accumulation by biennial sweetclover, when used as a green manure or if harvested only once during the seeding year, generally exceeds that of alfalfa and red clover (Kroontje and Kehr, 1956; Bowren et al., 1969; Groya and Sheaffer, 1985;), accumulating up to 348 kg N ha^{-1} (Groya and Sheaffer, 1985).

The measurement of legume N accumulation, although useful for comparing legume species or management strategies, is not a direct estimation of the N contribution from a legume to a subsequent non-legume crop. In some cases, the amount

of N accumulated by legumes has little, if any, positive relationship to dry matter yield or total N uptake of the following crop (Kroontje and Kehr, 1956; Hoyt and Leitch, 1983; Hesterman et al., 1986; Bruulsema and Christie, 1987). The value of legumes as an N source to a subsequent crop in rotation is more commonly estimated as an N fertilizer replacement value (FRV), defined as the "quantity of fertilizer N required to produce a yield in a crop that does not follow a legume that is identical to that produced by incorporation of the legume" (Hesterman, 1988). Estimates of FRV's from extensive research on legume-corn systems range from 13 (red clover; Fribourg and Bartholomew, 1956) to approximately 200 kg N ha^{-1} ('MN ROOT N' alfalfa; Hesterman et al., 1986). There are no FRV estimates available specifically for potato following a legume, although examples of potato yield increases of 10-50% following legumes, compared to potato monocultures or non-legume rotations, are not uncommon (Purvis and Blume, 1939; Wheeler, 1946; Terman, 1949; Murphy et al., 1967; Emmond and Ledingham, 1972). In Michigan, the "N credit" (analogous to FRV) for legumes preceding potato is adapted from the estimate for corn, ranging from 60 to 100 kg N ha^{-1} in proportion to the percent stand of the legume crop (Vitosh, 1990).

Research is needed to assess the contribution of N from legumes to a subsequent potato crop and to evaluate potato N fertilizer management following legumes. The specific objectives of this research were: (*i*) to compare N accumulation by forage legumes used as either green manure (no harvest during the seeding year) or hay (harvested 2 or 3 times during seeding year); (*ii*) to evaluate the effect of first year legume species and management and N accumulation on tuber and vine yield parameters of a subsequent potato crop grown without N fertilizer; and (*iii*) to determine N fertilizer response of potato following legumes, corn, fallow, and potato.

MATERIALS AND METHODS

Two-year crop rotations were established in 1987 at two Michigan locations; the Michigan State University Montcalm Research Farm at Entrican, and the Kellogg Biological Station (KBS) at Hickory Corners. Soil types were McBride sandy loam (Alfic Fragiothods) at Montcalm, and Oshtemo sandy loam (Typic Hapludalfs) at KBS. At Montcalm only, K_2O was applied at a rate of 170 kg ha^{-1} to all plots prior to beginning the experiment according to soil test results (Table 1.1). Subsequent soil tests indicated that no additional P or K was required at either location for the duration of the experiment. First year crops included: 'Saranac' alfalfa, 'Michigan Mammoth' red clover, 'Viking' birdsfoot trefoil, 'common' sweetclover, spring seeded 'common' hairy vetch, 'Pioneer 3737' corn, potato ('Shepody' and 'Atlantic' at Montcalm and KBS, respectively), and potato followed by fall-seeded hairy vetch. 'Nitro' alfalfa replaced sweetclover at KBS, and an uncropped fallow treatment was included at both locations. Due to drought conditions early in the 1987 growing season (Table 1.2), irrigation (80 mm) was applied as a rescue treatment at both locations in late June; crops were otherwise grown under non-irrigated conditions during 1987.

Legume management. Legumes were seeded into 7.6 by 15.2 m plots, using a grain drill (11 rows, 0.18 m row spacing) with a legume seed box and packer wheels, on April 18 and 28, 1987, at Montcalm and KBS, respectively. Fall-seeded hairy vetch (following potato) was planted on September 20 and 21, 1987, at Montcalm and KBS, respectively. Seeding rates were: birdsfoot trefoil, 6 kg ha^{-1}; alfalfa, red clover, and sweetclover, 15 kg ha^{-1}; and hairy vetch, 31 kg ha^{-1}. Two plots per

Table 1.1. Initial soil characteristics† at the Michigan State University Montcalm Research Farm and the Kellogg Biological Station (KBS).

Location	Bray-1 P	Exchangeable K	Ca	Total N	Organic matter	CEC	pH
	--------- kg ha^{-1} ---------			------ g kg^{-1} -----		cmol kg^{-1}	
Montcalm	579	311	849	5.9	15	5	5.9
KBS	315	569	2240	8.7	16	9	6.6

† Sampled in April, 1987.

Table 1.2. Mean monthly precipitation and air temperature at the Michigan State University Montcalm Research Farm and the Kellogg Biological Station (KBS).

		Precipitation			Air Temperature		
Location	Month	1987	1988	Long-term mean†	1987	1988	Long-term mean†
		---------- mm ----------			---------- °C ----------		
Montcalm	April	46	46	82	10	6	8
	May	49	13	72	17	16	14
	June	21	14	86	20	20	20
	July	46	61	63	24	23	22
	August	245	86	96	20	23	21
	September	83	134	78	17	16	17
	TOTAL	490	354	477			
KBS	April	60	77	88	11	9	9
	May	34	36	79	17	17	15
	June	51	37	105	23	22	20
	July	65	106	85	24	25	22
	August	176	127	89	22	24	21
	September	132	163	75	18	18	18
	TOTAL	518	546	521			

† Long-term (1950-1981) means from National Weather Service Stations at Greenville, MI, and Hickory Corners, MI, for Montcalm and KBS, respectively.

replication of alfalfa, red clover, and birdsfoot trefoil were planted. One was managed as a green manure crop not harvested during the seeding year. The other was managed as a hay crop, harvested two (birdsfoot trefoil) or three (alfalfa, red clover) times during the seeding year. 'Nitro' alfalfa at KBS was managed as a hay crop, and sweetclover (at Montcalm) and hairy vetch were managed as green manure. No pre-plant incorporated herbicide was used for legume seedings at either location. Broadleaf weeds in alfalfa, red clover, and birdsfoot trefoil were controlled with a single application of 2,4-DB [4-(2,4-dichlorophenoxy)butanoic acid] at 1.12 kg a.i. ha^{-1}, applied when the legumes were at the first trifoliolate stage.

Legumes managed as hay crops were harvested with a flail-type plot harvester. Fresh forage yield was determined by harvesting a 1.2 by 15.2 m strip from the center of each plot, and weighing the total sample. Dry matter content of forage was determined by drying a subsample (approximately 500 g), for 4 days at 60C. At harvest, random grab samples were clipped at ground level and separated into forage legume and weed components, to determine the proportion of pure forage legume in the harvested sample. Because of the high proportion of weeds in some treatments, forage and weed yields are reported separately. Alfalfa and red clover were harvested on July 10, August 14 and October 16 at Montcalm, and on July 11, August 13, and November 5 at KBS. Birdsfoot trefoil was harvested on July 20 and October 16 at Montcalm, and July 11 and November 5 at KBS. Spring regrowth of hay crop legumes was not harvested as hay prior to incorporation via moldboard plowing in May, 1988.

Dry matter and N content of legumes at the end of the seeding year was estimated by sampling four 0.33 by 0.33 m quadrats $plot^{-1}$ (after a killing frost) on October 14, 1987, at Montcalm and October 29, 1987, at KBS. Growth during the interval between biomass sampling and hay harvest (2 days at Montcalm, 6 days at

KBS) was considered to be negligible, because a killing frost had occurred at both locations. The N yield of the hay removed was subtracted from the pre-harvest legume N content. Plants were excavated to 0.25 m (plow depth) and separated into herbage and roots plus crowns. Roots were washed thoroughly to remove soil, and all plant material was dried for 4 d at 60C and weighed. All plant material was ground to 1 mm in a cyclone mill. Total N content of herbage and roots plus crowns was determined by micro-Kjeldahl digestion of 0.10g plant material in 12*M* H_2SO_4 (catalyzed by 1.5g K_2SO_4 and 0.075g Se), followed by colorimetric determination of NH_4^+ by Lachat Quik-Chem Method No. 10-107-06-2-E (Lachat Chemicals, Inc., Mequon, WI.). Legumes were sampled in the same way on May 3 (Montcalm) and May 5 (KBS), 1988, immediately prior to plowing, to determine the dry matter and N content of spring regrowth. Root N content declined an average of 15% at Montcalm and 24% at KBS through the winter. Thus, plowdown N (PDN) yield, defined as

$$\text{PDN} = \text{fall 1987 (herbage N + root N) + spring 1988 (herbage N)} \qquad [1]$$

was used here as a measure of the minimum amount of N accumulated by legumes prior to incorporation.

<u>Corn and potato management, 1987.</u> First-year corn and potato were planted on May 5 and 12, 1987, at Montcalm and KBS, respectively. Corn was planted at 60,000 seeds ha^{-1}, without herbicide or starter fertilizer, and was cultivated twice to control weeds. Corn whole plots (7.6 by 15.2 m) were split into four subplots (3.8 by 7.6 m), and fertilized with 0, 75, 150, or 225 kg N ha^{-1} (as ammonium nitrate), broadcast after planting. In October, grain was harvested from a 7.0 m section of the center two rows in each four row subplot. Stover was removed from harvest area, weighed, and five plants were taken as a subsample. After drying and grinding

subsamples, total N content of stover and grain was determined by micro-Kjeldahl digestion as described above.

Potatoes were planted in 0.92 m rows, with 0.25 m spacing between seed pieces weighing approximately 100g. Aldicarb {2-methyl-2-(methylthio)propanal-*O*-[(methylamino) carbonyl]oxime} was applied at planting at 3.36 kg a.i. ha^{-1} to control nematodes. Weeds were controlled with metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] and metribuzin [(4-amino-6-(1,1-dimethylethyl)-3-methylthio)-1,2,4-triazin-5(4*H*)-one], applied preemergent at 2.24 and 0.56 kg a.i. ha^{-1}, respectively. The same split N rates as applied to corn were broadcast on potatoes prior to emergence. Yield was determined by harvesting the center two rows of each subplot on September 1 and 4 at Montcalm and KBS, respectively.

Potato management, 1988. Following moldboard plowing in early May, 1988, potato ('Shepody') was planted in all whole plots on May 5 at KBS, and during May 12-14, at Montcalm. Row spacing, spacing of seed pieces, and pesticide applications (ie. aldicarb, metolachlor and metribuzin) were identical to those in 1987. All whole plots were split into subplots fertilized with the same N rates used in 1987. For subplots receiving N fertilizer, 75 kg N ha^{-1} was applied at planting, and the remainder, if any, was sidedressed prior to hilling. Irrigation (250 mm at KBS, 350 mm at Montcalm) was applied based on precipitation and evapo-transpiration (Vitosh, 1984). At Montcalm, irrigation began on June 3, and 18 to 20 mm was applied every 5 to 7 d until early August. At KBS, irrigation (25 to 35 mm $application^{-1}$) commenced on June 11, and was applied every 7 to 9 d, except for a 12 d period in late June when the irrigation well was broken. Foliar fungicide and insecticide were applied as needed during the growing season. Potato vine growth was sampled on August 25 and 30 (90 to 95 days after emergence) at Montcalm and

KBS, respectively, because of clear visual differences in vine growth following different rotation crops. In addition, previous research has shown that maximum vine DM and N content generally occurs between 80 and 100 d after emergence (Jackson and Haddock, 1959; Saffigna and Keeney, 1977). Vines from four hills were cut at soil level and weighed: A subsample was dried, ground to 1 mm, and total N content was determined by micro-Kjeldahl digestion. Dry matter and N content of vines are reported based on mean stand counts of 42,500 and 40,700 hills ha^{-1} at Montcalm and KBS, respectively. The center two rows were harvested from each subplot during September 30-October 5, 1988 at Montcalm. Harvest was delayed until November 15, 1988, at KBS because of high rainfall (300 mm) during September and October, 1988. Thus, one row per plot was harvested following only alfalfa green manure, alfalfa hay, red clover hay, spring seeded hairy vetch, corn, and potato. Tubers were graded by hand into; 'A' grade (114 to 281 g), 'B' grade (<114 g), oversize (>281 g), and cull (second growth, soft rot, etc.).

Experimental design and statistical analysis. Experimental design was a randomized complete block with four replications. Treatments were arranged in a split-plot design; 1987 crops were whole plots, and N fertilizer rates were sub-plots. Significant differences ($P<0.05$) in N accumulation by legumes, as indicated by analysis of variance, were separated using Least Significant Difference (LSD; Steel and Torrie, 1980). Where possible, significant effects were further partitioned using single degree of freedom orthogonal contrasts. The effect of fertilizer N rate on potato vine and tuber yield parameters was first evaluated within each rotation using single degree of freedom orthogonal contrasts (linear, quadratic, and cubic); significant responses to N rate were further evaluated by regression of potato yield (vine or tuber) on N rate. If the effect of rotation crop was not significant in the analysis of variance, mean N response across rotations was evaluated as described.

RESULTS AND DISCUSSION

Forage production by hay crop legumes. Forage dry matter (DM) yield and N concentration (total N production/total DM production) of alfalfa ('Saranac' at Montcalm; 'Saranac' and 'Nitro' at KBS) and red clover were significantly higher than birdsfoot trefoil on common harvest dates and for total seeding year production (Table 3). Because of the poor competitive ability of birdsfoot trefoil in the seedling stage and the lack of chemical weed control, weed competition at both locations was severe; about 80% of the total biomass at the fall harvest on birdsfoot trefoil plots was composed of weeds. At Montcalm, the total DM production and weighted N concentration for seeding year alfalfa and red clover were not significantly different, although the DM yield of alfalfa was lower for the first harvest (July 9) and higher for the second harvest (August 13), compared to red clover (Table 1.3). The total DM yield of alfalfa (mean of 'Saranac' and 'Nitro') at KBS was significantly higher than red clover (6698 vs. 6154 kg ha^{-1}). Hoyt and Leitch (1983) and Groya and Sheaffer (1985) also found that the total seeding year hay yield of alfalfa generally exceeds that of red clover. 'Saranac' alfalfa yielded more than the nondormant 'Nitro' alfalfa, in contrast to Hesterman et al. (1986) and Groya and Sheaffer (1985), who found that yields of dormant and non-dormant alfalfa varieties were similar. Both of these studies also reported higher forage yields for alfalfa than were observed here. In our research, soil moisture may have been limiting during the seeding year, even with supplemental irrigation in late June. Total precipitation plus irrigation from April through July, 1987, was only 80% of the long-term mean.

Table 1.3. Seeding year dry matter (DM) forage and weed yield and nitrogen (N) concentration of alfalfa, red clover, and birdsfoot trefoil harvested for hay at Montcalm and KBS in 1987.

Location	Harvest	Component	DM yield: 'Saranac' alfalfa	DM yield: 'Nitro' alfalfa	DM yield: Red clover	DM yield: Birdsfoot trefoil	Legume N concentration: 'Saranac' alfalfa	Legume N concentration: 'Nitro' alfalfa	Legume N concentration: Red clover	Legume N concentration: Birdsfoot trefoil
			$kg\ ha^{-1}$				$g\ kg^{-1}$			
Montcalm	1	Legume	2086	---	2224	497	32.6	---	31.1	25.7
		Weed	561	---	161	2043				
	2	Legume	1895	---	1204	---	41.2	---	35.1	---
		Weed	953	---	627	---				
	3	Legume	2203	---	2234	247	31.8	---	34.5	24.8
		Weed	0	---	0	970				
	Total legume		6184	---	5661	744	35.0	---	33.4	25.1
KBS	1	Legume	2369	1524	1779	93	32.3	33.1	34.4	22.1
		Weed	289	244	878	1492				
	2	Legume	2384	2287	2305	---	34.1	31.6	32.5	---
		Weed	439	365	745	---				
	3	Legume	2325	2521	2075	175	25.6	29.6	26.0	20.6
		Weed	0	0	0	511				
	Total legume		7078	6317	6154	268	30.7	30.9	30.8	21.1

Orthogonal contrasts

Location	Variable	Alfalfa + red clover vs. birdsfoot trefoil	Alfalfa vs. red clover	'Saranac' vs. 'Nitro'
		PR>F		
Montcalm	Total DM yield	***	NS	---
	Total weighted N concentration	***	NS	---
KBS	Total DM yield	***	*	*
	Total weighted N concentration	***	NS	NS

*,**,*** Significant at 0.05, 0.01, and 0.001, respectively. NS = not significant at 0.05 level.

Nitrogen accumulation by legumes. Among green manure crops at Montcalm, sweetclover and red clover had similar PDN yields (238 and 225 kg N ha^{-1}, respectively), which were significantly higher than either alfalfa or birdsfoot trefoil (Table 1.4). Spring-seeded hairy vetch accumulated nearly as much N (211 kg ha^{-1}) as sweetclover or red clover, despite experiencing complete winterkill after the seeding year, with 93% of the N accumulated in the 1987 herbage. (Fall-seeded hairy vetch was not successfully established at Montcalm, and thus was eliminated from the analysis.) At KBS, red clover green manure accumulated more N than hairy vetch (spring- or fall-seeded) and birdsfoot trefoil. Fall-seeded hairy vetch, which is commonly used as a winter cover crop in the southern U.S. (eg. McVay et al., 1990), accumulated only 33 kg N ha^{-1} at KBS, mostly in the spring herbage. This minimal accumulation of N, and the unsuccessful establishment at Montcalm, were a result of the late seeding date for fall-seeded hairy vetch. Further research in Michigan has shown that hairy vetch should be seeded prior to August 15 to ensure survival through the winter (Hesterman and Harris, 1990; unpublished data). This early seeding requirement makes it difficult to use hairy vetch as a cover crop in a cropping system following potato or corn.

Estimates of N accumulation by green manure legumes in short rotations have been based largely on seeding year N accumulation sampled prior to fall plowing (Kroontje and Kehr, 1956; Stickler et al., 1958; Bruulsema and Christie, 1987), or in some cases, on N content at incorporation for overwintering legume cover crops (Fleming et al., 1981; McVay et al., 1989). In our research, N content at either fall sampling or pre-plow sampling alone underestimates the amount of N accumulated by the legumes. So although it is difficult to directly compare the plowdown N yield of legumes, as defined here, with previous research, seeding year N accumulation (fall herbage plus fall roots; Table 1.4) can be compared with previous estimates.

Table 1.4. Nitrogen (N) content in herbage and roots in fall, 1987 and spring, 1988, and total plowdown N (PDN) yield of green manure (GM) and hay crop legumes at Montcalm and KBS.

Location	Legume/management	N content: Fall herbage	Fall roots	Spring herbage	Spring roots	PDN†
		kg ha^{-1}				
Montcalm	Alfalfa GM	68	75	46	51	189
	Alfalfa hay	51	70	51	50	172
	Red clover GM	127	58	40	49	225
	Red clover hay	53	76	34	51	163
	Birdsfoot trefoil GM	29	24	17	28	70
	Birdsfoot trefoil hay	21	18	10	17	49
	Sweetclover GM	93	96	48	90	238
	Hairy vetch GM	197	14	0	0	211
	$LSD_{0.05}$	29	19	11	20	34
KBS	Alfalfa GM	39	71	48	48	158
	Alfalfa hay	41	109	80	82	230
	'Nitro' alfalfa hay	26	92	48	80	166
	Red clover GM	105	47	50	68	202
	Red clover hay	37	94	98	84	229
	Birdsfoot trefoil GM	20	14	14	22	48
	Birdsfoot trefoil hay	15	18	15	18	48
	Hairy vetch (spring) GM	105	11	17	11	133
	Hairy vetch (fall) GM	2	1	20	12	33
	$LSD_{0.05}$	29	19	29	33	56

† PDN = fall (herbage N + root N) + spring herbage N.

Nitrogen content of alfalfa green manure at the end of the seeding year was similar to that of 'Indian', 'African', and 'Ranger' alfalfas established under similar conditions (Stickler et al., 1958). It was considerably lower, however, than recent estimates by Groya and Sheaffer (1985) and Bruulsema and Christie (1987), where pre-plant herbicides were used to control weeds. Nitrogen accumulation by red clover and sweetclover (at Montcalm) was higher than reported by Stickler and Johnson (1959) and Stickler et al. (1958), but lower than from Groya and Sheaffer (1985), who found 224 and 348 kg N ha^{-1}, respectively, in these two species at the end of the seeding year.

Seeding year harvest of birdsfoot trefoil (at both locations), alfalfa at Montcalm, and red clover at KBS did not significantly affect PDN yield, compared to the green manure crop of the same species. This information, coupled with the reduction in weed biomass at successive harvests of alfalfa and red clover (Table 1.3) shows that periodic clipping of green manure crops (herbage returned to soil) may reduce weed competition without reducing N accumulation (as shown by Groya and Sheaffer, 1985). This type of clipping management of green manure crops is particularly applicable to short rotations where the expense of herbicides may not be justifiable. The weed biomass data in Table 1.3 also show that the harvest in early August eliminated weed competition from the final fall harvest of alfalfa and red clover.

Seeding year harvest of red clover at Montcalm did reduce the PDN yield from 225 to 163 kg ha^{-1}, due primarily to removal of herbage in the fall (1987) harvest. Bruulsema and Christie (1987) found that a single summer harvest of alfalfa or red clover during the seeding year did not significantly affect the amount of legume N incorporated in the fall (compared to the unharvested treatment), because adequate time was given for regrowth prior to plowdown. The removal of alfalfa or red clover herbage in the fall, however, has been shown to reduce the amount of N incorporated (fall plowing) compared to green manure or summer harvest only (Groya and Sheaffer, 1985; Hesterman et al., 1986).

At KBS, 'Saranac' alfalfa as hay had a higher PDN yield than either 'Nitro' alfalfa as hay or 'Saranac' as green manure (Table 1.4). All hay crop legumes at KBS had a higher root N content in the fall of the seeding year than the green manure crop of the same species, although 'Saranac' alfalfa was the only species to exhibit a significant difference. Stickler and Johnson (1959) also saw an increase in fall root N content for alfalfa that had been clipped during the seeding year, which they attributed to a reduction in weed competition. Similarly, the increase in fall root N of alfalfa at KBS may be due, in part, to reduced weed pressure (although end-of-season weed biomass was not determined for green manure crops).

Potato yield without N fertilizer. The effect of previous crop on the N concentration, DM content and N content of the vines of the subsequent potato crop was significant ($P<0.05$) at both locations. Single degree of freedom orthogonal contrasts were utilized to partition the general effects of rotation ('rotation vs. potato'; Table 1.5), legumes ('legume vs. non-legume'), and legume management ('GM vs. hay legumes') on these vine yield parameters. Vines accumulated more DM in the rotations than in the potato-potato system at both locations, and more N in the rotations at KBS. This was due to the promotion of vine DM accumulation in the legume-based rotations. The mean vine N concentration, DM content, and N content following legumes was significantly higher than the mean values following non-legumes. In some cases (eg. sweetclover), N content was 2 to 3-fold higher following a legume than a non-legume. However, there were exceptions to this generalization. For example, vine N content following red clover green manure and hay and birdsfoot trefoil hay at Montcalm (N content=33, 28, and 23 kg ha^{-1},

Table 1.5. Effect of 1987 crop on vine nitrogen (N) concentration, and dry matter (DM) and N production of 1988 potato crop, grown without N fertilizer, at Montcalm and KBS† in 1988.

Location	1987 crop	Vine N concentration	Vine DM yield	Vine N yield
		$g\ kg^{-1}$	------------ $kg\ ha^{-1}$	------------
Montcalm	Alfalfa GM‡	25.2	2307	57
	Alfalfa hay	28.1	1747	49
	Red clover GM	24.0	1432	33
	Red clover hay	22.8	1229	28
	Birdsfoot trefoil GM	23.3	1891	45
	Birdsfoot trefoil hay	19.9	1182	23
	Sweetclover GM	27.6	3184	95
	Hairy vetch GM	27.9	3022	87
	Corn	21.0	1061	21
	Potato	20.7	1426	30
	Fallow	20.2	1445	30
KBS	Alfalfa GM	27.6	2379	65
	Alfalfa hay	33.0	3414	114
	'Nitro' alfalfa hay	25.7	2861	73
	Red clover GM	28.5	2895	82
	Red clover hay	30.0	3587	106
	Birdsfoot trefoil GM	24.3	2031	50
	Birdsfoot trefoil hay	25.2	3006	76
	Hairy vetch GM (spring)	26.8	2606	70
	Hairy vetch GM (fall)	26.4	1959	50
	Corn	24.4	1795	45
	Potato	24.5	1615	40
	Fallow	25.0	2510	61

Orthogonal contrasts

Location	Contrast	Vine N concentration	Vine DM yield	Vine N yield
		------------------------	PR>F	------------------------
Montcalm	Rotation vs. cont. potato	NS	*	NS
	Legumes vs. non-legumes	*	**	**
	GM v. hay legumes	NS	***	**
KBS	Rotations vs. cont. potato	NS	*	**
	Legumes vs. non-legumes	*	**	***
	GM vs. hay legumes	NS	**	***

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively. NS = Not significant at 0.05 level.
† Sampled on August 25 and 30, 1988, at Montcalm and KBS, respectively.
‡ GM = green manure, not harvested in 1987.

respectively) was similar to that following non-legumes (mean N content= 27 kg ha^{-1}).

The vegetative response of potato to legume N has not previously been documented. The promotion of vegetative growth late in the growing season following legumes such as seen here has been observed when excess fertilizer N was available during tuber bulking and maturation. Ojala et al. (1990), in a review of potato N and irrigation management, stated that "excessive nitrogen fertilizer application during tuber bulking can promote late-season vegetative growth and delay tuber maturity." Lauer (1985) examined N uptake by potato receiving from 150 ("deficient") to 610 ("excessive") kg N ha^{-1}, and found that the excessive N rate promoted both vine dry matter and N accumulation later in the growing season, although the effect on tuber yield was not discussed.

Direct measurements of soil inorganic N level late in the growing season, or of N mineralization rates within different rotations, were not determined in our research. However, the vegetative response of potato to legume is clear. Potato vine N content and the PDN yield of the preceding legume crops were significantly correlated at both locations, with correlation coefficients (r) of 0.41 (P=0.01, n=32) at Montcalm and 0.55 (P=0.001, n=36) at KBS. This indicates that 1) sufficient residual N was available following legumes to sustain vine growth later into the growing season, and 2) the magnitude of the response was affected by the amount of N in the previous legume crop. This relationship between vine N and legume N may be partially responsible for the difference in the effect of legume management at the two locations. At Montcalm, where green manure legumes accumulated more N than hay crops of the same species, vines accumulated more DM (P=0.001; 'GM vs. hay legumes') and more N (P=0.007) following green manure than following hay crops. At KBS, the opposite effect was observed; vine DM and N content was higher following hay crop legumes, which had higher PDN yields than the respective green manure crops.

Although N accumulation by legumes during 1987 and early 1988 ranged from 33 to 238 kg ha^{-1}, no significant differences in tuber yield between rotations were observed at either location when no N fertilizer was applied to the second year potato crop. Mean total, marketable ('A' grade plus oversize), 'B' grade, and cull yields were 28.5, 25.7, 1.8, and 1.0 Mg ha^{-1}, respectively, at Montcalm, and 27.4, 22.8, 1.5, and 3.0 Mg ha^{-1}, respectively, at KBS. The lack of tuber yield response to rotation in our research is in contrast to the results of Odland and Sheehan (1957) and Emmond and Ledingham (1972). In these two studies, increases in total tuber yield ranged from 13% following red clover (Odland and Sheehan, 1957) to 25% following sweetclover (Emmond and Ledingham, 1972), compared to continuous potato. Because each of these studies consisted of numerous rotation cycles, it is unclear whether the yield increases were due a contribution of N from the preceding legume crop or to non-N effects associated with the legumes. Using no N fertilizer, O'Sullivan and Reyes (1980) demonstrated that non-N effects may also be important in potato rotations, as potato yield increased from 17.6 (potato-potato) to 26.4 Mg ha^{-1} (corn-potato), although an N contribution from corn would not be expected.

Preceding a non-legume crop with an N-fixing legume does not always lead to higher non-legume yield (eg. Kroontje and Kehr, 1956; Fleming et al., 1981; Hesterman et al., 1986), as shown by our results. In our research, there are two potential causes for the lack of tuber yield response to rotation, given the marked vegetative response discussed above. First, although a considerable amount of N is contained in the incorporated legume material, mineralized legume N may not accumulate in sufficient quantity during early vegetative growth to affect the number and survival of tuber initiates. Potato is most sensitive to insufficient or excess soil N during the critical period of tuber initiation, and differences in N fertility during this period ultimately influence the yield and quality of the potato crop (Roberts et al., 1982; Ojala et al., 1990). Alternatively, the lack of tuber yield response to legume N may indicate that some factor other than soil N level was limiting during tuber initiation and/or early tuber bulking. The dry spring in 1988 may have led to a soil moisture deficit, especially following legumes that utilized available soil moisture in the spring, that was not overcome until tuber initiation had taken place.

Potato N response in rotation. The availability of residual soil N late in the growing season, from legumes or fertilizer, is apparent from differences in vine DM and N content and vine N concentration. Because these three parameters responded similarly to both N sources, only vine N content is presented here. The effect of fertilizer N rate on vine N content was not significant following fallow and hairy vetch at Montcalm (mean N content = 75 and 120 kg ha^{-1}, respectively) and following alfalfa hay, birdsfoot trefoil hay, and spring- and fall-seeded hairy vetch at KBS (mean N content = 85, 77, 92, and 68 kg ha^{-1}, respectively). At Montcalm, the response of vines to N fertilizer was similar following alfalfa (green manure or hay) and birdsfoot trefoil, so the mean response of these rotations is shown (ALF-BGM) in Figure 1.1. Given the low PDN yield of birdsfoot trefoil green manure (70 kg N ha^{-1}), the similarity in response to that following alfalfa may be due to the mineralization of N from weed biomass in the trefoil plots. Potato vines following sweetclover contained nearly 50% more N than following alfalfa or birdsfoot trefoil green manure (at all N rates), and twice as much N as following red clover, birdsfoot trefoil hay, corn, or potato (mean response as RC-BHY-C-P in Figure 1.1).

Vine N content following 'Nitro' alfalfa at KBS was greater than following any other crop at N rates from 75 to 225 kg ha^{-1} (Figure 1.2). Significant vegetative

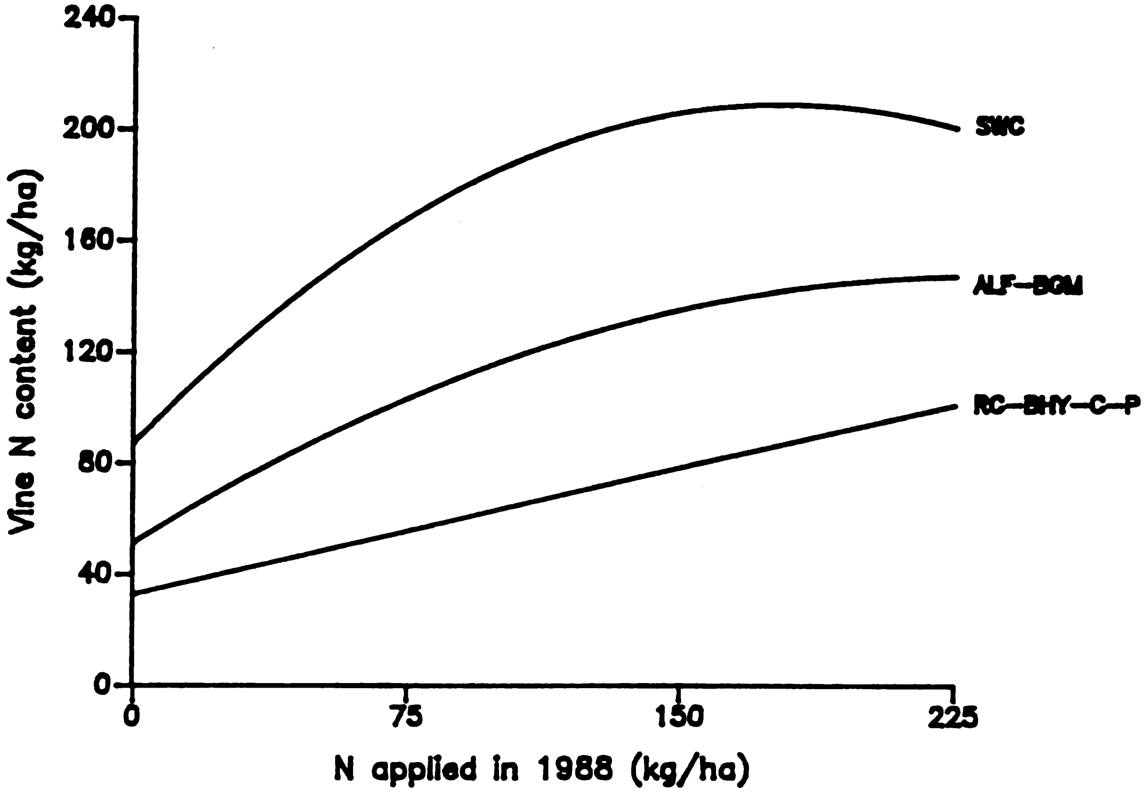

Figure 1.1. Effect of N fertilizer rate on late-season (August 25, 1988) potato vine N content following: alfalfa and birdsfoot trefoil green manure (mean response, ALF-BGM); red clover, birdsfoot trefoil hay, corn, and potato (mean response, RC-BHY-C-P); and sweetclover (SWC) at Montcalm. [Regression equations for ALF-BGM, RC-BHY-C-P, and SWC, respectively: $Y=51.08+0.826N-0.00176N^2$, $R^2=0.99$; $Y=32.4+0.305N$, $R^2=0.98$; and $Y=87.17+1.364N-0.00308N^2$, $R^2=0.88$, where Y=vine N content (kg ha^{-1}) and N=fertilizer N applied (kg ha^{-1}).]

responses to N fertilizer among other legumes (red clover, and alfalfa and birdsfoot trefoil green manures) were nearly identical, except when no N fertilizer was applied. Vine N content was lower following non-legumes (fallow, corn, and potato) than following legumes, as was the case at Montcalm, suggesting that there is an additive effect of legume and fertilizer N on vegetative response.

Total, marketable, 'B' grade, and cull tuber yields of potato at KBS in 1988 were not affected by the previous crop or the 1988 N fertilizer rate, averaging 27.6, 22.7, 1.8, and 3.1 Mg ha^{-1}, respectively. The lack of tuber yield response to both of these factors strongly suggests that, despite scheduled irrigation applications, soil moisture was limiting during at least the first half the growing season. The 12 d period in late June, when irrigation was not available, may have been particularly harmful, since this is the period of tuber initiation. The susceptibility of potato to drought is well documented (eg. van Loon, 1981). The results of Ojala et al. (1990) show that as "total seasonal water" increased from 161 to 586 mm, total tuber yield increased approximately five-fold, and the yield response to residual plus fertilizer N also increased. Miller and Martin (1985) found that deficit irrigation prior to June 14 did not reduce total tuber yield measured at the end of the season (mid-September). However, tuber weight was significantly lower throughout most of the growing season (to August 4) as a result of the early season deficit, and vine dry matter was higher in plots receiving insufficient irrigation.

There were few significant responses to previous crop and N fertilizer rate at Montcalm. The yield of 'B' grade tubers was similar for all treatments (mean 'B' yield = 1.6 Mg ha^{-1}), and no significant correlation existed between 'B' grade yield and any other tuber or vine yield parameter. Gardner and Jones (1975) and Tyler et al. (1983) also found that even as total tuber yield increased with N rate, 'B' grade yield remained relatively constant across N rates. Malformed tubers (primarily

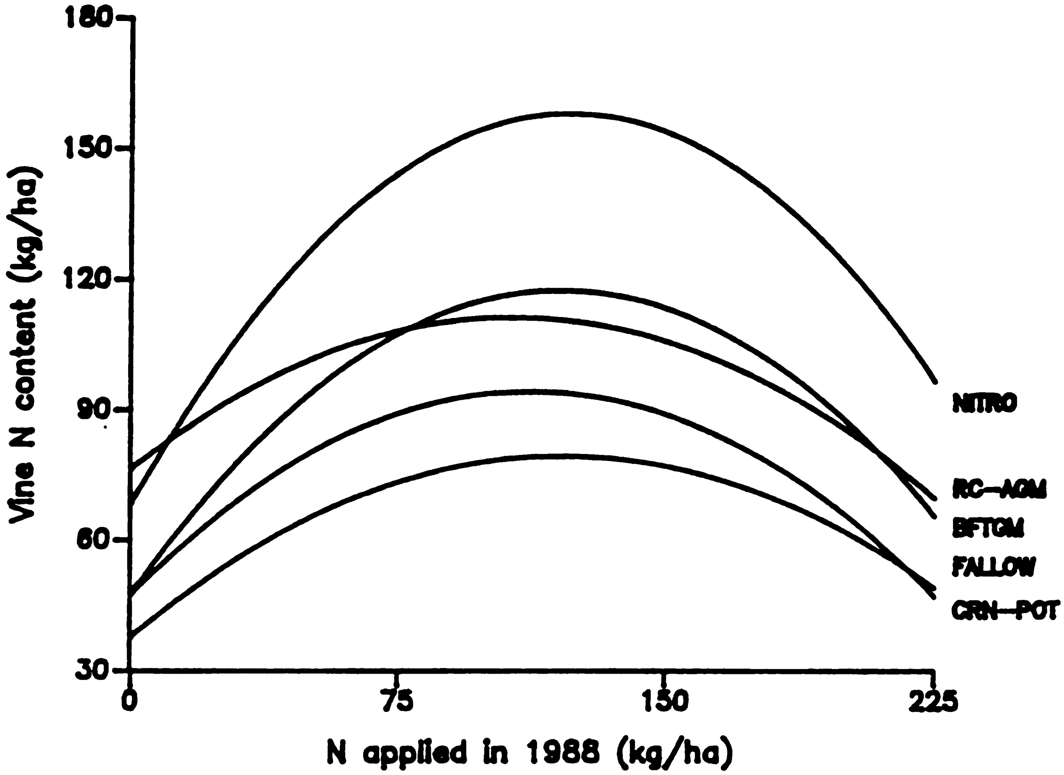

Figure 1.2. Effect of N fertilizer rate on late-season (August 30, 1988) potato vine N content following 'NITRO' alfalfa, red clover and alfalfa green manure (mean response, RC-AGM), birdsfoot trefoil green manure (BFTGM), FALLOW, and corn and potato (mean response, CRN-POT) at KBS. [Regression equations for NITRO, RC-AGM, BFTGM, FALLOW, and CRN-POT, respectively: $Y=68.42+1.46N-0.00592N^2$, $R^2=0.92$; $Y=76.4+0.65N-0.00303N^2$, $R^2=0.87$; $Y=47.5+1.16N-0.00418N^2$, $R^2=0.98$; $Y=47.4+0.84N-0.00372N^2$, $R^2=0.90$; and $Y=37.7+0.69N-0.00283N^2$, $R^2=0.75$, where Y=vine N content (kg ha^{-1}) and N=fertilizer N applied (kg ha^{-1}).]

tubers exhibiting second growth) indicate either intermittent nutrient supply and/or the sudden relief of plant stress during tuber bulking (Robins and Domingo, 1956; Hiller et al., 1985). Cull yield increased with N rate in all systems except hairy vetch-potato (cull yield=3.0 Mg ha^{-1}), and was significantly higher following sweetclover (SWC; Figure 1.3) than any other crop. Hiller et al. (1985) discussed the potential causes of tuber malformation, which included excessive vegetative growth. We found that cull yield for all rotations and N rates *was* significantly correlated with vine DM and N content and N concentration (r=0.419, 0.519, and 0.481, respectively; P<0.001)). However, this correlative relationship may arise simply because excessive vine growth and tuber malformation are symptomatic of excess N, not because they are (necessarily) related.

Total tuber yield following alfalfa, birdsfoot trefoil, sweetclover and spring-seeded hairy vetch exhibited no significant response to fertilizer N, averaging 30.9 Mg ha^{-1}. Using the corn-potato rotation as a control (regression equation in Figure 1.4), these legumes replaced 69 kg ha^{-1} of N fertilizer, according to the FRV technique described by Hesterman (1988). Total yield of potato following fallow or potato increased linearly with N rate (Figure 1.4). Maximum yield following red clover (mean of green manure and hay crops) and corn required approximately 150 kg N ha^{-1}, slightly below the 170 kg ha^{-1} rate recommended for potato in Michigan (Vitosh, 1990). The effect of N rate on marketable tuber yield was most pronounced in the corn-potato rotation (Figure 1.5), with maximum marketable yield requiring approximately 150 kg N ha^{-1}, similar to optimum N rates reported by Murphy et al. (1967), Gardner and Jones (1975), and O'Sullivan (1978), and the recommended rate in Michigan (Vitosh, 1990). The reduction in marketable yield at the highest N rate was due primarily to an increased proportion of malformed tubers. The effect of rotation on marketable yield was not significant for the other rotations; thus the

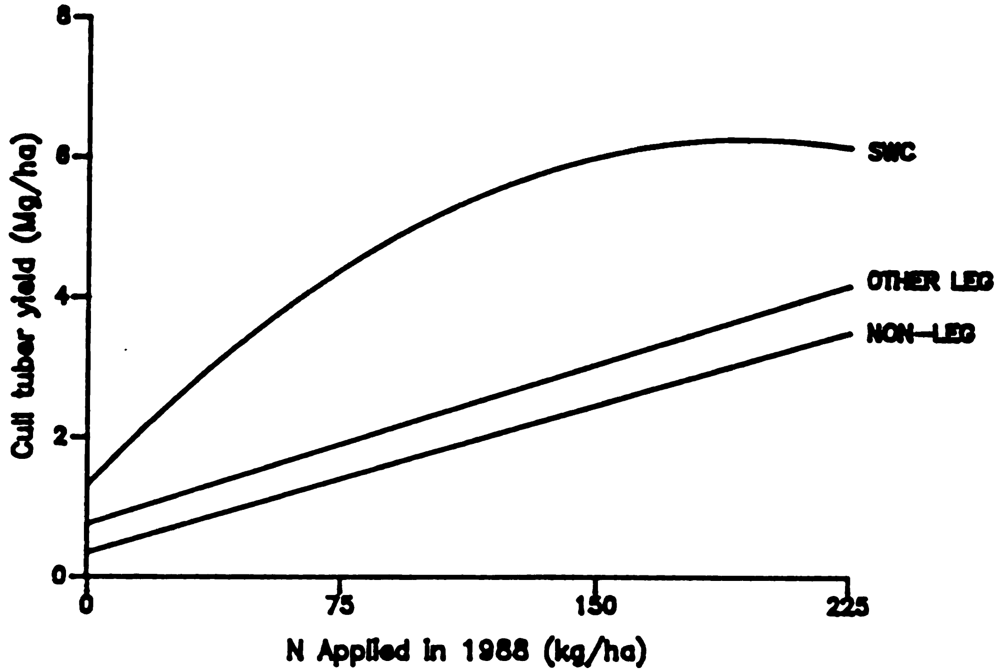

Figure 1.3. Effect of N fertilizer rate on cull tuber yield following sweetclover (SWC), other legume crops (OTHER LEG; mean of alfalfa, birdsfoot trefoil, hairy vetch, and red clover) and non-legume crops (NON-LEG; mean of corn, fallow, and potato) at Montcalm. [Regression equations for SWC, OTHER LEG, and NON-LEG, respectively: $Y=1.32+0.051N-0.00013N^2$, $R^2=0.99$; $Y=0.746+0.015N$, $R^2=0.99$; and $Y=0.338+0.014N$, $R^2=0.94$, where Y=tuber yield (Mg ha^{-1}) and N=fertilizer N applied (kg ha^{-1}).]

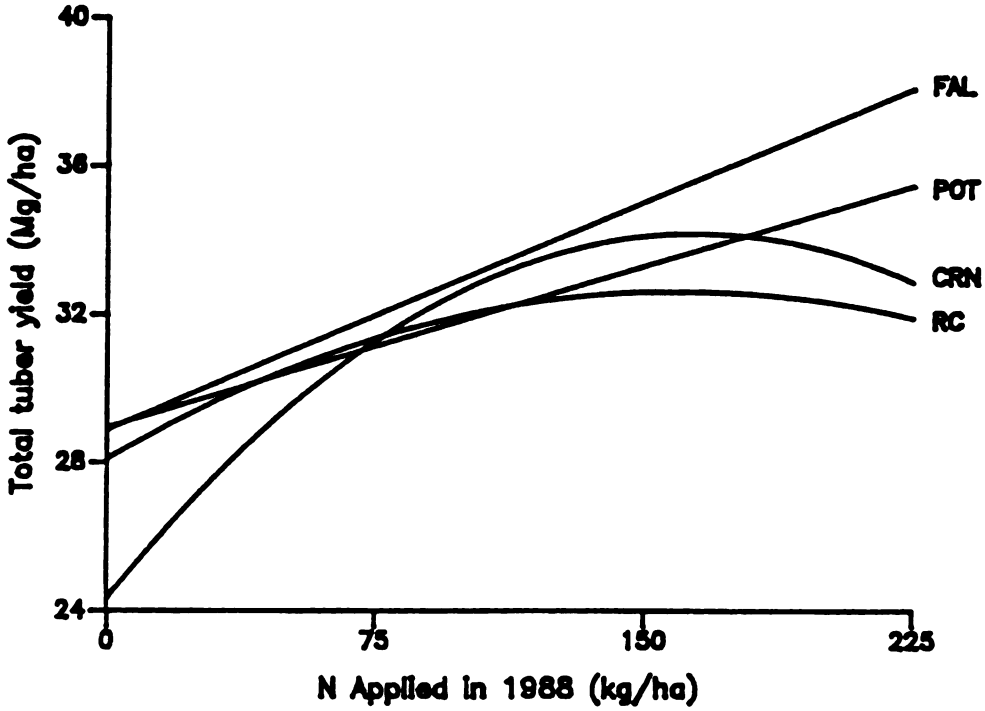

Figure 1.4. Effect of N fertilizer rate on total potato tuber yield following corn (CRN), fallow (FAL), potato (POT), and red clover (RC), at Montcalm. [Regression equations for CRN, FAL, POT, RC, respectively: $Y=24.33+0.12N-0.00036N^2$, $R^2=0.97$; $Y=28.87+0.0413N$, $R^2=0.98$; $Y=28.93+0.0292N$, $R^2=0.84$; $Y=28.08+0.567N-0.000176N^2$, $R^2=0.87$, where Y=tuber yield (Mg ha^{-1}) and N=fertilizer N applied (kg ha^{-1}).]

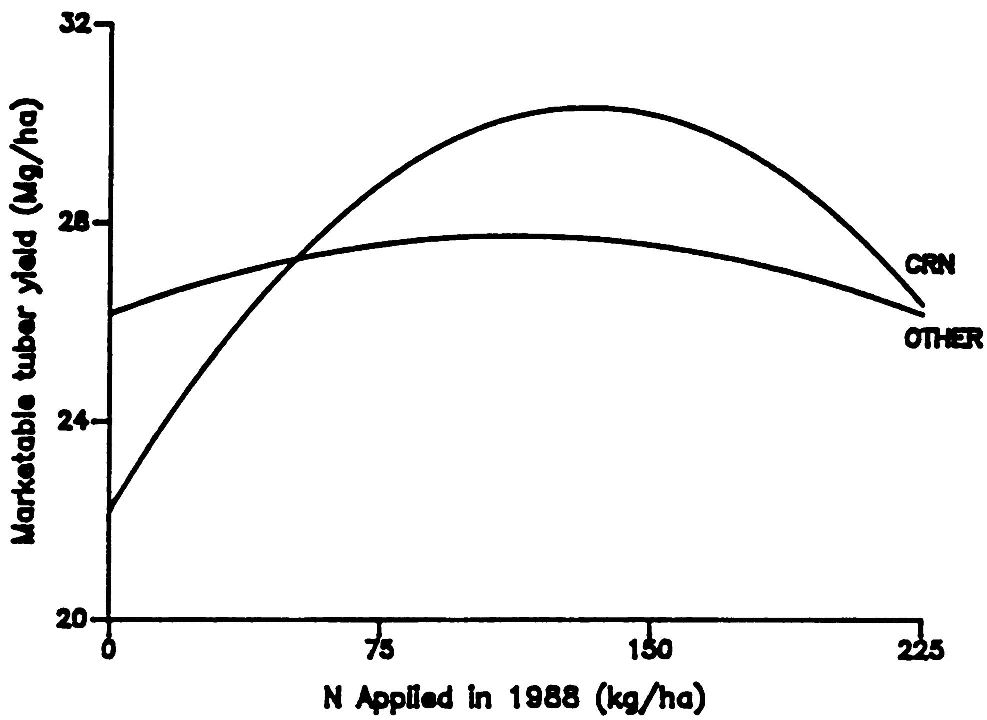

Figure 1.5. Effect of N fertilizer rate on marketable tuber yield following corn (CRN) and all other crops (mean response, OTHER) at Montcalm. [Regression equations for CRN and OTHER, respectively: $Y=22.21+0.122N-0.000463N^2$, $R^2=0.90$; and $Y=26.15+0.28N-0.00012N^2$, $R^2=0.81$, where Y=tuber yield (Mg ha^{-1}) and N=fertilizer N applied (kg ha^{-1}).]

mean N response is shown (OTHER; Figure 1.5). Murphy et al. (1967) examined potato yield at each of six N rates (67 to 235 kg ha^{-1}) following potato, red clover, and red clover plus oat (*Avena sativa* L.). They found that within each N rate, previous crop had no significant effect on tuber yield. O'Sullivan (1978) observed that potato N response following corn or potato was nearly identical, except that yield was slightly higher following corn.

SUMMARY

In our research, we found that seeding year harvest of legumes was not necessarily detrimental to N accumulation, compared to a green manure crop of the same species. For alfalfa, birdsfoot trefoil, and red clover at two locations, only red clover at Montcalm exhibited a significantly lower PDN yield due to seeding year harvest. Furthermore, periodic harvests served to reduce weed competition with alfalfa and red clover (but not birdsfoot trefoil). This type of management should also be considered for weed control in green manure crops, where clipping has been shown to increase total N production (Stickler and Johnson, 1958; Groya and Sheaffer, 1985).

We observed a pronounced vegetative response to legume N by the subsequent potato crop, grown without N fertilizer. The higher vine DM and N content (following legumes) late in the growing season is evidence that N from incorporated legumes eventually becomes available to the potato crop. However, the lack of *tuber* yield response to legume N indicates that either there is a lack of synchrony between legume N availability and potato N demand or that available N was not the limiting factor in potato yield. The response of the potato crop to fertilizer N in different rotations at Montcalm helps to distinguish between these alternatives. A significant tuber yield response to fertilizer N was observed in only one legume-based rotation at Montcalm; red clover-potato. If the lack of tuber response to legume N was due to asynchrony in supply and demand, the addition of N fertilizer would be expected to elicit an increase in tuber yield (as in the corn-potato rotation, for example). This not being the case, the lack of tuber response to legume N, and to fertilizer N following legumes, is attributed to a soil moisture deficit induced by legume growth during the dry spring in 1988. Even with supplemental irrigation, this deficit was apparently not overcome until after tuber initiation had occurred.

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CHAPTER TWO

ECONOMIC COMPARISON OF ALFALFA-POTATO, CORN-POTATO, AND CONTINUOUS POTATO SYSTEMS

ABSTRACT

Crop rotations for high-value crops like potato (*Solanum tuberosum* L.) will be implemented only when the economic viability of such systems is demonstrated. Monte Carlo computer simulations were used here: (*i*) to compare the magnitude and variability of net income from alfalfa (*Medicago sativa* L.) green manure-potato, alfalfa hay-potato, and corn (*Zea mays* L.)-potato rotations and continuous potatoes, assuming normal distributions for prices and yields; and (*ii*) to evaluate the effect of reduced mean yield and skewness (positive and negative) on the net income from continuous potatoes. In a baseline simulation to compare rotational and continuous potato production systems, continuous potatoes had a higher mean annual net income ($498/a), with more variability (standard deviation, σ=$372/a), than any rotational system. The alfalfa hay-potato rotation generated more net income ($312/a) than the alfalfa green manure-potato or corn-potato rotations ($226 and $276/a, respectively), although absolute variability was similar for all rotations (σ=$200/a). A 15% reduction in continuous potato yield (to 255 cwt/a), simulating the long-term yield decline commonly seen in continuous potatoes, resulted in a mean net income ($322/a) nearly identical to that from the alfalfa hay-potato rotation. However, net income variability was 37% higher for continuous potatoes, confirming that monocultural production carries greater economic risk than rotations, even at the

same mean net income. The introduction of positive skewness (gamma distribution) into potato yield did not affect mean net income or income variability, compared to a normal distribution, when both distributions had a mean of 270 cwt/a and σ=34 cwt/a. However, if potato yield exhibited negative skewness (beta distribution), mean net income and variability both increased, as did potential loss (minimum net income= -200, -158, and -$250/a for normal, gamma and beta distributions, respectively). The implementation of potato rotations for agronomic reasons depends most strongly on the assumptions that potato yield in monoculture declines with time. The simulations performed here demonstrate that if continuous potato yield declines more than 15%, rotations (with alfalfa or corn) generate more net income, with less variability, than a continuous potato system.

INTRODUCTION

The potential agronomic benefits from growing potatoes or other crops in rotation with nitrogen (N)-fixing legumes have been demonstrated, and include: N contribution from legumes to subsequent potato crops (Emmond and Ledingham, 1972); improved soil structure and water infiltration (Odland and Sheehan, 1957; Saloman, 1962); and disruption of pest and weed cycles (Brodie et al., 1969; Weinhold et al., 1964). Evidence that agricultural practices lead to environmental pollution, particularly nitrate and pesticide contamination of groundwater, coupled with an interest in reducing non-renewable, petroleum-based inputs in potato production, have increased interest in crop rotations for environmental reasons. The adoption of rotational production systems by producers on a large scale, however, will occur only when the economic viability of these systems is demonstrated. Two criteria that have been useful in comparing the economics of different cropping systems are the *magnitude* and *variability* of net income (gross income minus variable cash costs).

A primary goal of agricultural production, like other business enterprises, is to provide an acceptable level of return to the producer for capital, labor, and management inputs. Linear programming and enterprise budgets have both been used to select the optimal production system from a set of alternatives (Heady et al., 1956; Helmers et al., 1986; Rowberry and Anderson, 1983). In some cases, higher net income has been demonstrated from legume-corn rotations than continuous monocultures of corn (Heady and Jensen, 1952; Hesterman et al., 1986). The profitability of legume-corn rotations resulted from either increased corn yields in rotation (eg. Heady and Jensen, 1951) and/or reduced production costs (eg.

Hesterman et al., 1986b) for the subsequent corn crop. Few economic analyses have been conducted evaluating rotations with intensively managed crops like potato, requiring high inputs of pesticide, labor, and capital. Rowberry and Anderson (1983) examined net returns of potato rotations with barley (*Hordeum vulgare* L.) and corn compared to continuous potatoes, and found that continuous potatoes provided the highest mean net income over a 7 yr period. A selection of optimal potato *rotations* under variable risk aversion was conducted by El-Nazar and McCarl (1986). They found that as risk aversion increased, the time period between potato crops in rotation also increased.

Income variability or risk plays an important, and often overlooked, role in economic decision-making by producers (Stovall, 1966). Expected income can be simply defined by:

$$E\ (\text{income}) = (P(Y))-C \qquad [1]$$

where P, Y, and C are the price, yield and production costs, respectively, of a specific crop. Risk is introduced into [1] because commodity prices and crop yields cannot be known with certainty until the crop is harvested and sold. Thus, both P and Y must be considered stochastic components, each with a characteristic (but unknown) probability distribution. This assumes that the variability in production costs is minimal compared to price or yield variability (Musser et al., 1981; Buccola, 1986). If only one crop is produced, variability in net income is defined as σ_I^2, following a multivariate distribution dependent on the variability in price and yield. However, the production of two (or more) crops, either through crop rotation or diversification, requires that variability in income be expanded to:

$$\sigma_I^2 = \sigma_i^2 + \sigma_j^2 + 2p\sigma_i\sigma_j, \quad \text{for } i \text{ and } j = 1 \text{ to } n \qquad [2]$$

(from Heady, 1952; p is the correlation of income between crop i and j) to include income covariance between different crops. The use of either rotational or diversified systems as an effective method of reducing income variability is based on the premise that if a strong positive correlation does not exist between the net income generated by different crops in rotation (ideally, $p \leq 0$), then reduced income from one crop is more likely to be accompanied by increased income from another crop (Heady, 1952; Stovall, 1966). This results in less drastic losses when low prices prevail and lower profits under high price conditions, compared to continuous monocultures.

Computer simulations, such as Monte Carlo techniques, are useful in establishing the probability distribution of net income from different enterprise combinations (eg. Buccola, 1986) when sufficient agronomic or production cost data are not available. For example, if the underlying price and yield distributions are estimated from detrended historical price and yield series (Pope and Ziemer, 1984; Tew and Reid, 1988), numerous combinations of price and yield can be used to generate a distribution of potential net incomes. Concerns have been raised, however, over the widely held assumption that variability in crop prices and yields follow normal distributions (King and Robison, 1981; Collender and Zilberman, 1985), and over the impact of this assumption on net income distribution (Tew and Reid, 1988). Research by Day (1962) demonstrated that long-term yield series commonly exhibit some degree of non-normality or skewness, which could ultimately affect the probability of attaining a certain level of income and the identification of optimal production systems.

Further investigation is needed on the economic viability of legume- or corn-potato rotations, compared to continuous potato production, and on the identification of the factors influencing the relative profitability of these systems. This research uses computer simulations to address these two broad areas. The economic evaluation is specifically for alternative potato production systems (ie. potatoes are grown at least every other year). The objectives of this research were: i) to determine the mean net income and variability in net income from alfalfa-potato, corn-potato and continuous potato systems assuming normal distributions of prices and yields; and ii) to examine the effect of reduced mean yield level and skewness on net income from continuous potato production.

MATERIALS AND METHODS

Monte Carlo simulations were performed to compare the expected mean net income and the variability in income of four production systems: alfalfa green manure-potato, alfalfa hay-potato and corn-potato rotations; and continuous potatoes. Enterprise budgets (Table 2.1) were established for each crop using information from Shapley and Williams (1988) for potatoes and Nott et al. (1988) for alfalfa and corn, with minor modifications. These budgets include variable production costs, but not fixed costs for land or machinery ownership. Nitrogen fertilizer rates are; 175 lb/a for potatoes following potatoes or corn, 100 lb/a for potatoes following alfalfa (Vitosh, 1990), and 110 lb/a for corn (Nott et al., 1988). All costs, revenues, and net incomes are calculated based on a farm size of 500 acres, slightly smaller than the average farm size for potato producers in Michigan (Shapley, 1987). All 500 acres are in potatoes for the POT system. The rotational systems have 250 acres in potatoes and 250 acres in either alfalfa or corn.

Table 2.1. Enterprise budgets for potatoes, corn, and seeding year alfalfa in Michigan.

Expense	Crop		
	Potatoes†	Corn‡	Seeding-year alfalfa‡
Yield goal	300 cwt/a	100 bu/a	3 ton/a
	$/acre		
Seed	150.00	19.60	26.25
Non-N fertilizer	49.92	10.80	30.00
N fertilizer	35.00 (20.00)§	22.00	0.0
Chemical costs			
Fungicide	64.10	0.0	0.0
Insecticide	73.43	2.20	3.00
Herbicide	63.44	13.00	8.75
Cultural labor¶	30.08	32.67	39.60
Fuel, oil#	70.00	9.90	8.00
Machinery repair	75.00	18.00	5.00
Utilities	20.00	2.50	1.50
Harvest, storage	99.86††	20.10‡‡	75.00‡‡
Packing, marketing	442.36††	1.00	0.00
Freight	0.0	12.00	22.40
Drying	0.0	12.00	0.0
TOTAL	1138.19 (1123.19)§	187.77	219.50

† Adapted from Shapley and Williams (1988).
‡ Adapted from Nott et al. (1988).
§ Cost of N fertilizer with reduced application rate following alfalfa (Vitosh, 1990).
¶ Labor for: planting, cultivation, irrigation and spraying, $5.50/hr.
# Includes fuel for potato irrigation.
†† Fixed harvest costs = $99.86/acre; variable harvest costs = $1.47/cwt.
‡‡ Custom harvest cost for corn. Schwab and Norgaard (1988).
‡‡ Custom harvest cost for alfalfa; $25.00/acre/harvest.

Crop yields. Mean yields of corn and potato were initially set at 100 bu/a and 300 cwt/a, respectively (Table 2.2). These yields levels were used in the cost publications cited above, but also approximate mean yields (1981 to 1988) from Montcalm county, MI, the primary potato producing county in the state (Michigan Agricultural Statistics). The variability in potato and corn yields was calculated as the standard deviation of the yield series (1981 to 1988) from Montcalm county (σ=38.1 cwt/a for potatoes and 12.9 bu/a for corn). Seeding year alfalfa hay yield from Nott et al. (1988) was estimated to be only 2.0 ton/acre. Recent research by Groya and Sheaffer (1985) and Hesterman et al. (1986a) in Minnesota suggested that such yields underestimate the seeding year yield potential of alfalfa. This was confirmed by Griffin and Hesterman (1990; unpublished data[1]), who achieved yields of 3.5 to 4.0 ton/acre on potato soils in Montcalm county. Thus the mean yield of alfalfa was set at 3.0 ton/acre (σ=0.3 ton/acre). All yield distributions summarized in Table 2.2 were assumed to be normal. Yield distributions were truncated at 210 and 360 cwt/a for potatoes and at 50 and 150 bu/a for corn, approximately 10% below and above the extremes observed in the yield time series, to simulate a realistic yield range for these crops in Michigan. Correlation coefficients between yields of potatoes, corn, and alfalfa hay (Table 2.3), required to construct variance-covariance matrices for simulations, were determined from statewide average yields of each crop (1981 to 1988) because alfalfa yields specific to Montcalm county were not available. As expected, corn and alfalfa hay yields were more highly correlated with each other than with potato yields, because corn and alfalfa are generally grown under dryland conditions, while potatoes are grown under irrigation.

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[1] See Chapter One, Table 1.3.

Table 2.2. Summary statistics of truncated normal yield distributions for potato, corn, and alfalfa hay.

	Crop		
	Potato	Corn	Alfalfa
Yield units	cwt/a	bu/a	ton/a
Mean	300	100	3.0
Standard deviation	38.1	12.9	0.3
Minimum yield estimate	210	50	1.5
Maximum yield estimate	360	150	4.5

Table 2.3. Simple correlation coefficients (_r_) between potatoes, corn, and alfalfa hay.

		Potato	Corn	Alfalfa
Crop yields				
			_r_	
	Potato	1.00	0.28	0.43
	Corn		1.00	0.83
	Alfalfa			1.00
Crop prices		Potato	Corn	Alfalfa
			_r_	
	Potato	1.00	0.69	0.57
	Corn		1.00	0.88
	Alfalfa			1.00

Crop prices. Nominal crop prices were compiled from the Michigan Agricultural Statistics reports (1981-1988), and adjusted to constant 1988 dollars (1988$) using the "Prices paid to producers" indices (USDA, 1989). Reliable estimates of the market price of alfalfa were not available. Thus, the alfalfa prices were calculated based on the cost of replacing the energy and protein in alfalfa with corn and soybean meal, respectively, according to Hesterman et al. (1988). Real crop prices (in 1988$; Table 2.4) were then used to calculate the mean and standard deviation in crop prices. Price distributions were assumed to be normal, and the null hypotheses of normality could not be rejected, based on the Shapiro-Wilks test (Shapiro and Wilk, 1965), for potato, corn or alfalfa hay prices. Correlations between the prices of the three products (potatoes, corn, and hay) are also shown in Table 2.4. The correlation between the price and yield of each crop was assumed to be zero, based on the assumption that total production from the farm was not sufficient to influence the market price (ie. perfect competition; El-Nazar and McCarl, 1986).

Monte Carlo simulations. Monte Carlo simulations were performed using the Agricultural Risk Management Simulator (ARMS; King et al., 1989). Following the input of production costs, price and yield distributions, and covariance between crops (for prices and yields), 250 random estimates were generated from the price and yield distributions of each crop. Net income (gross income minus cash costs) was calculated from paired price and yield estimates according to equation [1], yielding a probability distribution of potential net incomes for each production system. The initial ("baseline") simulation comparing rotations (AGM, AHY, and CRN) with continuous potatoes (POT) was performed using normal distributions for all crop prices and yields (described in Tables 2.2 and 2.3).

Table 2.4. Prices for potatoes, corn, and alfalfa hay in Michigan, 1981-1988 (adjusted to 1988$).

Year	Crop		
	Potato	Corn	Alfalfa
	$/cwt	$/bu	$/ton
1981	4.66	1.90	79.7
1982	4.61	2.42	85.4
1983	6.65	2.56	99.1
1984	4.50	2.05	74.5
1985	4.40	2.05	74.8
1986	6.36	2.44	86.1
1987	5.47	2.69	110.2
1988	8.00	2.60	94.9
Mean	5.58	2.34	88.1
Standard deviation	1.31	0.29	12.5

There is ample agronomic evidence that yield levels in continuous potato monocultures cannot be maintained with constant inputs of fertilizer and pesticide,with the decline in potato yield over time generally being attributed to increased disease severity in monoculture (McDole and Dallimore, 1978; O'Sullivan and Reyes, 1980). Long-term yield series for continuous potatoes are not available for Michigan to examine the economic impact of such a trend. Thus, a simulation (n=250) was conducted to asses the effect of declining mean potato yield on net income. Holding pre-harvest and fixed harvest costs constant, potato yields were reduced in 5% increments (15 cwt/a) to 75% of the baseline level of 300 cwt/a. The coefficient of variation (σ/mean) was held constant at 12.7% as potato yield fell, and each yield distribution was truncated at 70 and 130% of the mean yield.

A third simulation was conducted to evaluate the effect of potato yield distribution on net income level and variability (potato price followed a normal distribution with mean=\$5.58/cwt and σ=\$1.31/cwt). Research by Day (1962) demonstrated that both positive and negative skewness was evident in crop yields over time, with the direction of skewness varying with crop species and management. Thus, a normal yield distribution was compared to two skewed distributions: a positively skewed gamma distribution approximated by $\alpha=\beta=2$ (coefficient of skewness=0.60); and a negatively skewed beta distribution approximated by $\alpha=5$ and $\beta=2$ (coefficient of skewness= -0.51). The parent distributions from which estimates were generated each had a mean of 270 cwt/a and σ=34.

RESULTS AND DISCUSSION

Rotational versus continuous potato production. The mean and variability of net income for the four production systems is summarized in Table 2.5. The 95% confidence interval limits associated with the mean and standard deviation of each

Table 2.5. Net income distribution for alfalfa green manure-potato, alfalfa hay-potato, and corn-potato rotations (250 acres of rotation crop, 250 acres of potatoes), and continuous potatoes (500 acres) assuming normal distributions of prices and yields.

	Production system			
	Alfalfa green manure-potato	Alfalfa hay-potato	Corn-potato	Continuous potato
	Net income, $1,000's			
Mean	113	156	138	249
Lower CI limit†	100	142	126	226
Upper CI limit	125	169	151	272
Standard deviation	99	106	100	186
Lower CI limit	92	98	92	172
Upper CI limit	109	117	110	205
CV, %	88	68	72	75
Net income range				
Minimum	-52	-32	-27	-55
Maximum	373	434	419	762

† CI = 95% confidence interval.

system, calculated according to Equations (3) and (4) in Collender (1989), are also shown. Based on this initial simulation, the alfalfa hay-potato rotation provided the highest mean net income ($156,000, for farm size=500 acres) *among rotational systems*, 12 and 28% higher than the corn-potato and alfalfa green manure-potato rotations, respectively. Although mean net income was significantly different for these three systems (AHY > CRN > AGM), absolute variability was similar for all rotational systems, with σ=$100,000. The higher relative variability of the alfalfa green manure system resulted because only one saleable product (potatoes) was produced. Thus, this system does not actually represent economic diversification of the farm operation, only a reduction in potato acreage. In addition, the potential contribution of N from the green manure crop to the subsequent potato crop (*circa* 75 lb/a) has a monetary value of $3750 (for 250 acres), compared to alfalfa establishment costs of about $30,000. The comparison made here between the two alfalfa-based rotations supports Hesterman et al. (1986b) and Allison and Ott (1987), who found that the value of alfalfa as a cash crop far exceeds its value as an N source for subsequent crops under current price and cost conditions.

The mean net income from continuous potatoes ($249,000) exceeded that from any rotational system. Rowberry and Anderson (1983) also found that continuous potatoes provided a higher mean income than rotations with barley, corn or soybeans (*Glycine max* Merr.). They did not, however, address the issue of income variability in continuous and rotational potato production systems. We found that in addition to a higher mean, net income from continuous potatoes was more variable (ie. higher standard deviation), with a greater potential for both profit and loss, than any of the rotations. Although our research does not directly address risk aversion, the selection of an appropriate potato production system would represent a compromise between these two factors, net income and variability, based on the preferences of the producer. El-Nazar and McCarl (1986) included risk aversion in their selection of optimal potato rotations in Oregon. They found that as producer risk aversion increased, 1) mean net income and variability decreased, and 2) the time span between potato crops increased, indicating that the potato phase of the rotations carried the greatest economic risk. Although we found that absolute variability increased with net income, as it usually does, relative variability was similar for the AHY, CRN, and POT systems, with a CV of approximately 70%. This conflicts with the results of Schurle and Erven (1979), who found that as the production of specialty vegetable crops increased, net income, absolute variability *and relative variability* all increased.

The increased variability associated with monocultures that we see here is not specific to potato production. The analysis of monocultural, rotational and diversified grain production systems by Helmers et al. (1986) showed that continuous corn had the highest standard deviation and the greatest range in net income, despite having the *lowest* mean net income. Likewise, continuous grain sorghum [*Sorghum bicolor* (L.) Moench.] had a higher standard deviation and CV than rotational production system. Schurle and Erven (1979) also found that net income from continuous corn production was more variable than from diversified systems including soybeans or wheat (*Triticum aestivum* L.).

<u>Effect of decreased continuous potato yield on net income.</u> From the simulation discussed above, we found that continuous potatoes were more profitable, with more variability, than alfalfa- or corn-potato rotations. However, it must be kept in mind that the crop yields utilized were based on statewide averages. On any particular farm, it is unlikely that continuous potato yield can be maintained over time at 300 cwt/a without substantial increases in chemical inputs (pesticides and/or fertilizer). Conversely, continuous potato yields are expected to decline if inputs

remain constant (Wheeler, 1946; Emmond and Ledingham, 1972; McDole and Dallimore, 1978; O'Sullivan and Reyes, 1980). A second simulation was thus conducted to examine the specific effect of decreasing continuous potato yield, varying only mean potato yield and costs directly related to yield level (ie. $1.47/cwt).

As expected, mean net income fell from $258,000 at 300 cwt/a to $116,000 at 225 cwt/a (Table 2.6), roughly following a linear trend. Thus a 25% reduction in mean potato yield resulted in a 55% reduction in mean net income. In comparison to the rotational systems shown in Table 2.5, continuous potatoes with a mean yield of 255 cwt/a (a 15% reduction from the baseline) generated a net income ($161,000) nearly identical to that from the alfalfa hay-potato rotation ($156,000). Agronomically, a 15% lower yield in a continuous versus rotational potato system is in agreement with the 12, 15, and 18% reductions for continuous potatoes (versus potatoes in rotation) reported by O'Sullivan and Reyes (1980), McDole and Dallimore (1978), and Emmond and Ledingham (1972), respectively. The variability in net income was considerably higher for continuous potatoes (σ=$168,000), with a mean yield of 255 cwt/a, compared to the alfalfa hay-potato rotation (σ=$106,000). This demonstrates that even at similar levels of net income, monocultural production inherently carries more economic risk than does a rotational system.

The mean and variance components in economic analyses, once calculated, are commonly considered non-stochastic in nature; ie. that the mean is constant over time with observations being randomly distributed around the mean value. In reality, it is likely that these components change over time (McSweeney et al., 1987). This concept seems particularly applicable to potato yield in monoculture, where the yield has been shown to decrease over time. The effect of such a change on mean net income is clearly shown in Table 2.6. However, the effect on income variability

Table 2.6. Mean and variability of net income from simulation (n=250) of continuous potato yield ranging from 225 to 300 cwt/a (potato yield normally distributed, coefficient of variation=12.9% for all yield levels).

	Mean potato yield (cwt/a)					
	225	240	255	270	285	300
	Net income, $1,000's					
Mean	116	136	161	207	224	258
Lower CI limit†	96	116	140	186	203	233
Upper CI limit	135	157	182	228	246	282
Standard deviation	154	163	168	168	177	195
Lower CI limit	145	150	155	155	163	180
Upper CI limit	173	179	184	184	195	215
CV, %	133	120	104	82	87	76
Net income range						
Minimum	-162	-134	-96	-83	-66	-100
Maximum	578	766	762	720	806	860

† CI = 95% confidence interval.

is much less dramatic; the same 25% reduction in the mean yield reduces the standard deviation of net income only 22%. Thus if potato yields decline in monoculture, the producer may be faced with lower net income levels without a proportional reduction in variability, thus increasing relative variability. Because producers are less likely to accept risk (ie. variability) at lower income levels (King and Robison, 1981), rotational systems are superior under these conditions.

Skewness in potato yield distributions. Net income from monocultural potato production is directly related to the yield of potatoes. As simplified in Equation [1], if yield, Y, falls without a proportional reduction in costs, C, net income also falls. The effect of skewed yields or prices on the distribution of net income is less certain and tends to be highly case specific. For example, Buccola (1986) demonstrated that net income may be skewed even though both price and yield are normally distributed. (This arises when the price and yield of a specific crop are correlated, an assumption not imposed here.) Alternatively, Tew and Reid (1988) found that income distribution may be normal when both price and yield exhibit significant skewness. Skewness was introduced into monocultural potato yields here because of the likelihood of skewness in yield distributions (Day, 1962) and because producer perception of risk is influenced by skewness (Collender and Zilberman, 1985). For each distribution, mean potato yield was 270 cwt/a and σ=34 cwt/a.

The imposition of positive skewness (following a gamma distribution) in potato yield did not significantly change mean net income or income variability compared to normally distributed potato yields (Table 2.7). The normally distributed yields did lead to greater potential loss than with positively skewed yields (minimum net income= -$100,000 and -$79,000, respectively). As discussed by Collender and Zilberman (1985), highly risk-averse producers favor positively skewed distributions over negative skewness or normality for this reason; low values are less likely while maintaining a long tail to the right (ie. high values from the distribution are not constrained).

Mean net income and the standard deviation of net income were higher for the negatively skewed potato yields (mean=\$228,000; σ=\$183,000) than normal or positively skewed yields. This distribution may be more appropriate for monocultural crop production because yields above the mean value are restricted (in this case, maximum yield was 320 cwt/a, compared to 350 cwt/a for the gamma distribution), while there is a greater potential for catastrophic yields to occur (minimum yield=180 cwt/a). However, there is no reliable data that indicate that this distribution more realistically describes monocultural potato yield over time in Michigan, compared to normal or positively skewed distributions. As a result of the long tail to the left of this beta distribution, the negatively skewed distribution also exhibited a greater potential loss (-\$125,000) than the other two yield distributions.

For the three potential distributions simulated here, we observed no consistent effect on relative income variability (CV=80 to 88%), and the imposition of skewed yield distributions did not result in skewed net income distributions. From this simulation, it is apparent that the effect of skewed yields on net income is less pronounced than the effects of the reduced mean yield levels examined in the previous simulation.

CONCLUSIONS

From the simulations performed here, we found that the profitability of rotational versus continuous potato production depends primarily on the potato yield level utilized. If the assumption is made, as it was in the initial simulation, that potato yield is unaffected by the preceding crop (ie. 300 cwt/a for all systems), continuous potato production generates more net income than any rotation.

Table 2.7. Effect of potato yield distribution on mean and variability of net income (mean yield = 270 cwt/a for all distributions).

	Yield distribution		
	Normal	Gamma, positively skewed	Beta, negatively skewed
	Net income, $1,000's		
Mean	183	199	228
Lower CI limit†	163	179	206
Upper CI limit	203	220	251
Standard deviation	161	165	183
Lower CI limit	149	152	169
Upper CI limit	177	181	201
CV, %	88	83	80
Net income range			
Minimum	-100	-79	-125
Maximum	662	726	833

† CI = 95% confidence interval.

As continuous potato yield was reduced from 15 to 20%, rotations were superior to continuous potatoes; they generated net income at a level similar to continuous potatoes, but exhibited less variability in net income. The comparison of the two alfalfa-based rotations shows that the use of alfalfa solely as an N source for potatoes (rather than as a cash crop and an N source) reduces net income more than 25%, without reducing income variability.

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CHAPTER THREE

EFFECT OF FORAGE LEGUMES ON PATHOGEN POPULATIONS AND TUBER QUALITY IN LEGUME-POTATO ROTATIONS

ABSTRACT

Research was conducted in Michigan in 1987-88 to evaluate the effect of forage legumes and corn on populations of *Pratylenchus penetrans* and *Verticillium dahliae*, and the influence legume-potato and corn-potato rotations and N fertilizer rate (0, 75, 150, 225 kg ha^{-1}) on potato scab, black scurf, growth cracking and specific gravity of tubers. First year rotation crops included alfalfa, red clover, and birdsfoot trefoil as green manure and hay crops, sweetclover and hairy vetch as green manure, and corn. Potatoes were grown on all plots in 1988.

All legumes (seeded in April, 1987) except sweetclover exhibited elevated populations of *P. penetrans* (143-638 *P. penetrans* per g root + 100 cm^3 soil) by July, 1987, compared to a corn-potato control. Population trends at the end of the growing season (November, 1987) were similar to those at mid-season. Despite high nematode populations under legume crops in November, 1987, no significant differences existed in soil *P. penetrans* population prior to planting potatoes in May, 1988. None of the first year rotation crops influenced soil inoculum levels of *V. dahliae*, which averaged 4 colony forming units (cfu) g^{-1} soil in May, 1988.

Red clover used as a hay crop in 1987 was associated with increased scab severity of the subsequent potato crop, with at least 50% more severely scabbed tubers than in other rotations. Incidence of black scurf following hairy vetch was 2

to 3-fold higher than following any other rotation crop. Growth cracking and specific gravity of tubers in 1988 were not affected by the previous rotation crops. Scab severity decreased in all rotations with increasing rates of N fertilizer (0 to 225 kg N ha^{-1}), while black scurf and growth cracking increased with N fertilizer rate to 150 kg ha^{-1}.

None of the rotations examined eliminated soil-borne pathogens or completely curtailed potato disease development, compared to corn-potato control. However, rotations including alfalfa or sweetclover did not increase the severity of potato scab or black scurf, and sweetclover exhibited lower nematode infestation than other legumes. In contrast, rotations including red clover hay or hairy vetch increased the severity of scab and black scurf, respectively, along with supporting higher nematode populations.

INTRODUCTION

The development of effective chemical pesticides, inexpensive nitrogen (N) fertilizer, and improved potato varieties have led to continuous potato (*Solanum tuberosum* L.) production on the same land in many places. Current concerns over the environmental and economic implications of high pesticide and N inputs in potato production have renewed interest in crop rotations, especially those including N-fixing legumes. However, there is little information available about the effect of alternative rotation crops based on either pathogen population trends during years when potatoes are not grown or tuber quality of the subsequent potato crop.

Pratylenchus penetrans (Cobb) Filipjev & Schuurmans-Stakh. is the most important nematode pathogen of potatoes on mineral soils in Michigan and is found on approximately 50% of the land used for potato production (Bird, 1981). The proliferation of *P. penetrans* during the growth of forage legumes in rotations with potatoes has justifiably caused concern over the potential damage to subsequent potato crops in rotation (Kimpinski, 1979). Nematode infection levels in excess of 10,000 *P. penetrans* g^{-1} root dry matter have been observed in legumes like alfalfa (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.). These infection levels have been associated with forage yield reductions of more than 50 percent (Willis and Thompson, 1969; Thompson and Willis, 1975). Although forage legumes are susceptible to, and alternative hosts for, *P. penetrans*, little information is available comparing population trends of this pathogen for different legume rotation crops.

There are several strategies for non-chemical control of *P. penetrans*. Like most soil-borne pathogens, populations of *P. penetrans* can be reduced by natural attrition if sufficient time elapses between susceptible crops (Emmond and Ledingham, 1972). However, the wide host range of *P. penetrans* (Brodie et al., 1969; Francl et al., 1988) makes the selection of non-host rotation crops difficult. *P. penetrans* populations may also be reduced by products released from decomposing plant residues, mainly NH_4^+ (Heald and Burton, 1968; Walker, 1971), and more diverse soil microbial communities associated with rotations (Linford et al., 1938; Jonhson et al., 1969).

It is also difficult to control *Verticillium dahliae* Kleb. and other fungal pathogens of potato using crop rotations. The long-term viability of *V. dahliae* microsclerotia in soil (Davis and McDole, 1978; Rowe et al., 1987) and the infection and colonization of weeds and other crops that do not develop typical wilt symptoms (Heale and Isaac, 1963) contributes to this difficulty. Infectivity and disease caused by *V. dahliae* is also influenced by *P. penetrans*. A synergistic interaction has been documented between *V. dahliae* and *P. penetrans*, where the presence of both pathogens causes more damage than the sum of pathogens separately (Martin et al., 1982; Riedel and Rowe, 1985; Rowe et al., 1987). Francl et al. (1988) found that *V. dahliae* and *P. penetrans* alone reduced tuber yield up to 31 and 16%, respectively, while yield was reduced up to 63% when both pathogens were present.

Streptomyces scabies (Thaxt.) Waks. & Henrici, the actinomycete that causes common potato scab, is also capable of long-term survival in the absence of a susceptible potato crop. Menzies (1963) classified *S. scabies* as a "normal soil inhabitant" because of its ability to feed and reproduce saprophytically when host plants were not present. The severity of common potato scab is influenced by the time period between potato crops and, in some cases, the crop rotation, although the effect of these two factors has been inconsistent. Increases in scab severity have been shown many times as either the time between potato crops is shortened or as more successive potato crops are grown (Goss and Afanasiev, 1938; Werner et al., 1944; Hooker, 1959). Wheeler (1946) also observed that scab increased with continuous potatoes, but potatoes following alfalfa or rye (*Secale cereale* L.) had significantly less scab than those following sweetclover (*Melilotus* spp.) or potatoes. Hooker (1959), however, found that the only crop to influence scab severity was potato. Because of the erratic control of scab with crop rotations, the most prevalent method of controlling scab has been to maintain soil pH at levels unfavorable to *S. scabies* (<5.0;Ellison et al., 1951) using ammonium-based N fertilizers.

Because of the diverse host range and saprophytic ability of *Rhizoctonia solani* Kuhn., research on cultural control practices has focused primarily on the composition of plant material incorporated immediately prior to a susceptible crop. *R. solani* has been controlled in many crops by incorporating plant material with a high carbon-to-nitrogen (C/N) ratio like barley (*Hordeum vulgare* L.) straw to immobilize soil N. Control has been observed at C/N ratios greater than 6 (compared to approximately 15 for alfalfa), but more commonly at C/N ratios of 40-200 (Davey and Papavizas, 1959, 1963). The inhibitory effect of high C/N ratio plant material has been attributed to the poor competitiveness of *R. solani* for soil N, which can be reversed by the application inorganic N fertilizer (Papavizas and Davey, 1960; Papavizas, 1970), and to increased populations of antagonistic fungi (Papavizas and Davey, 1960).

The research reported herein examines differences in pathogen populations and disease severity in two-year rotational potato systems, and was conducted within the framework of a field experiment on nitrogen management in legume-potato rotations. No treatments were imposed to specifically influence populations of soil-borne pathogens, as short rotations are unlikely to adequately control any of the pathogens discussed here. Rather, rotation systems were evaluated for their potential to *increase* pathogen populations and disease severity. Specifically, the objectives of this research were: 1) to monitor *P. penetrans* and *V. dahliae* populations during and immediately following legumes in two-year legume-potato rotations; and 2) to evaluate the effect of first year rotation crop and second year N fertilizer rate on common scab severity, incidence of Rhizoctonia, and growth cracking and specific gravity of tubers in the subsequent potato crop.

MATERIALS AND METHODS

Crop production practices. Research was initiated in 1987 at the Michigan State University Montcalm Research Farm, near Entrican, MI, to examine pathogen populations trends and disease severity in legume-potato rotations. The experiment was conducted on a McBride sandy loam soil (coarse-loamy, mixed, frigid Alfic Fragiothods). Initial soil test results indicated: pH 5.9; 311, 579, and 849 kg ha^{-1} of K, P, and Ca, respectively; organic matter, 15 g kg^{-1}; and CEC of 5 cmol kg^{-1} soil.

Alfalfa ('Saranac'), red clover ('Michigan Mammoth'), birdsfoot trefoil (*Lotus corniculatus* L. 'Viking'), common sweetclover (common), hairy vetch (*Vicia villosa* Roth, common) and corn (*Zea mays* L.'Pioneer 3737') were planted as first year rotation crops. Two treatments each of alfalfa, red clover, and birdsfoot trefoil were planted; one managed as a green manure left unharvested during the seeding year, and the other managed as a hay crop harvested two (birdsfoot trefoil) or three (alfalfa and red clover) times during the seeding year. Corn plots were divided into four subplots fertilized with 0, 75, 150, or 225 kg N ha^{-1}, as ammonium nitrate (NH_4NO_3). Establishment and harvest procedures for legumes and corn are described elsewhere (Griffin & Hesterman, 1990; manuscript in preparation[1]).

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[1] See Chapter One, pp. 6-12.

Following plowing on May 5, 1988, all plots (8 rows by 15.2 m) were planted to potatoes ('Shepody'), with a row spacing of 0.92 m, and seed pieces 0.25 m apart. Aldicarb (Temik 15G) was applied at 3.4 kg ai ha^{-1} at planting. Split-plot N rates (same as 1987) were applied as 75 kg N ha^{-1} at planting and the remainder, if any, sidedressed prior to hilling on May 26, 1988. Metolachlor (Dual) and metribuzin (Lexone) were applied preemergence at 2.2 and 0.56 kg ai ha^{-1}, respectively. Foliar insecticides and fungicides were applied to potatoes as needed during the growing season. During September 30-October 6, 1988, the center two rows of each subplot were harvested, and tubers were separated into; 'B' grade (<114 g), 'A' grade (115-280 g), oversize (>281 g), and culls (second growth, soft rot, etc.).

Soil and plant sampling for pathogens. Soil samples were taken 4 times during the first year of the rotations to determine soil population densities of *P. penetrans*. Legume plots and corn plots that received no N fertilizer were sampled on May 5, July 23, November 5, 1987, and May 12, 1988. These subplots were sampled to evaluate the effect of rotation crop species independently of N fertilizer management. Fifteen to twenty 2.5 cm dia by 20 cm deep soil cores were taken randomly in each plot. Cores were composited, mixed thoroughly, and subsampled (approximately 500 g) for analysis.

P. penetrans was extracted from soil using the centrifugation-flotation technique (Jenkins, 1964). Root samples were taken on July 23 and November 5, 1987, to determine root infestation of different rotation crops by *P. penetrans* by the shaker-incubation method. Soil samples taken in May, 1988, were also used to determine pre-plant inoculum levels of *V. dahliae*, using the dilution plate method described by Nicot and Rouse (1987), with an alcohol agar medium (Nadakavukaren and Horner, 1959).

Evaluation of tuber quality. Samples of approximately 5 kg of 'A' size tubers were collected from each N rate subplot in 1988 for evaluation. Ten tubers were randomly selected from each sample, thoroughly washed, and evaluated for severity of common potato scab. Each of the ten tubers was placed in one of five scab severity classes based on the percent of tuber surface area exhibiting scab lesions; 0-1, 1-5, 5-10, 10-25, and more than 25%. A weighted average scab severity was then calculated for each rotation crop/N rate combination.

The same ten tubers used for scab evaluation were also evaluated for black scurf and growth cracking. If black scurf was observed on any of the ten tubers, a value of 100 was recorded; absence of black scurf was recorded as zero. The number of tubers (out of ten) exhibiting growth cracks was also recorded. Specific gravity was determined by the weight in air to weight in water ratio on 2 kg of tubers from the original sample.

Experimental design was a randomized complete block with 4 replications. Treatment design was a split plot, with 1987 rotation crop as whole plots and 1988 N fertilizer rate as split plots. Rotation crop means were compared using Least Significant Difference (LSD) or Duncan's Multiple Ranges test (DMRT). LSD or DMRT were not calculated unless main effect was significant at 0.10 level. Statistical analyses of *P. penetrans* populations were performed on square root transformed data to equalize the variance among treatments. N rate means were compared using linear and quadratic orthogonal contrasts.

RESULTS AND DISCUSSION

P. penetrans populations in rotations. The pre-plant population density (P_i) of *P. penetrans* in the soil of individual plots at the beginning of the two-year rotations (May, 1987) was similar across the experimental area, ranging from 38 to 60 *P. penetrans* 100 cm^{-3} soil.

By mid-season (July, 1987), significant differences were observed in population densities of *P. penetrans* associated with the different rotation crops (Table 3.1). Among legume crops, sweetclover supported the lowest *P. penetrans* population, while hairy vetch supported the highest (60 and 638 *P. penetrans* 100 cm^{-3} soil + g^{-1} root, respectively). This agreed well with the observations of MacDonald and Mai (1963) who observed population increases of 112 and 358% for sweetclover and hairy vetch, respectively. Populations associated with the remaining legume crops were similar, exhibiting 3 to 8-fold increases from P_i in May, 1987. In contrast to the increases in *P. penetrans* in legume treatments, populations under the growing corn crop were lower than P_i.

By November, 1987, there were differences in *P. penetrans* populations associated with both rotation crop species and green manure or hay crop management of the same species. Relative population levels between rotation crops in November were similar to those found in July, 1987. Sweetclover and hairy vetch still supported the lowest and highest *P. penetrans* populations, respectively, among legume crops. Likewise, *P. penetrans* in soil and roots of corn plots was lower than all legume species. The low population level associated with corn was contrary to the results of Dickerson et al. (1964), who observed more rapid root infection and

Table 3.1. Effect of rotation crops on population densities of *Pratylenchus penetrans* and *Verticillium dahliae* in 1987-1988 at the Michigan State University Montcalm Research Farm in Entrican, MI.

	P. penetrans 100 cm^{-3} soil + g^{-1} root				*V. dahliae* colony forming units g^{-1} soil
Rotation Crop	5/87†	7/87	11/87	5/88†	5/88
Alfalfa GM‡	43	143bcd§¶	112ef	10	4.0
Alfalfa Hay	50	424ab	161def	18	4.0
Red Clover GM	48	335ab	202cde	32	2.5
Red Clover Hay	38	278bc	454ab	21	3.0
B. Trefoil GM	57	269bc	435abc	6	5.5
B. Trefoil Hay	44	375ab	308bcd	18	3.5
Sweetclover GM	47	60cd	107ef	21	5.0
Hairy Vetch GM	44	638a	679a	43	3.5
Corn	48	27d	47f	7	5.0
Prob.>F	NS	0.012	0.0001	NS	NS

† Population density for soil only.

‡ GM = Green Manure, no harvest during seeding year

§ Means with same letter in each column are not statistically different at 0.10 level using Duncan's Multiple Range test.

¶ Duncan's Multiple Range test performed on square root transformed data.

population growth by *P. penetrans* on corn than on potato.

The effect of legume harvest management on the population of *P. penetrans* was minimal. At the end of the seeding year, red clover hay supported a higher population than red clover managed as a green manure (Table 3.1), but no significant differences due to legume harvest were seen for alfalfa or birdsfoot trefoil. Research comparing legumes used as green manure and hay is limited, but MacDonald and Mai (1963) reported that infestation of hairy vetch and many other crops by *P. penetrans* increased as defoliation became more severe. Although we found that all legumes supported high populations of *P. penetrans*, other research has indicated that yield reductions are unlikely because losses caused by *P. penetrans* were usually delayed until the second or third production year (Willis and Thompson, 1969; Thompson and Willis, 1975).

No statistically significant differences in *P. penetrans* populations (soil only) due to 1987 rotation crop were detected immediately prior to planting the 1988 potato crop. Although no significant differences existed, the lowest and highest populations (7 and 43 *P. penetrans* 100 cm^{-3} soil) were observed following corn and hairy vetch, respectively. The similarity in *P. penetrans* soil populations immediately prior to planting potatoes means that, although high populations were associated with most legume crops in 1987, this would have little impact on the subsequent potato crop.

V. dahliae soil inoculum levels following different crops. There were no differences in soil inoculum levels of *V. dahliae* midway through the rotation cycle (May, 1988, immediately prior to the susceptible potato crop) related to the 1987 rotation crop (Table 3.1). As reported previously (eg. Davis and McDole, 1978; Rowe et al., 1987), the absence of a susceptible potato crop for periods of 1 to 3 years is not sufficient to reduce the soil population of this pathogen. The experimental area utilized had grown potatoes every second or third year for many years, and levels of *V. dahliae* in this area are sufficient to cause damage to susceptible crops. A mean soil inoculum level of 4 colony forming units (cfu) *V. dahliae* g^{-1} air-dried soil was observed.

Tuber evaluation of 1988 potato crop. No significant rotation crop by N rate interaction was observed for any tuber quality parameter examined. Thus, main effects of rotation crop and N rate will be discussed separately.

Although potatoes had not been grown in this experimental area for three years prior to initiating rotations in 1987, symptoms of common scab were prevalent on the 1988 potato crop (consistently in excess of 5%, below which is considered acceptable for marketable tubers). This may be partially due to the use of a scab-susceptible potato variety ('Shepody') in 1988. Because of the high incidence of potato scab, data are reported as percent of 'A' grade tubers exhibiting scab lesions on more than 25% of surface area.

Averaged across N rates, scab severity was influenced slightly ($P=0.09$) by the previous rotation crop (Table 3.2). Twenty-eight percent of tubers following red clover, as a hay crop, were severely scabbed. Rouatt and Anderson (1950) also noted that scab severity following red clover was similar to that in continuous potato, and much higher than in soybean (*Glycine max* Merr.)-potato rotations. Scab following red clover was significantly higher than following alfalfa green manure, birdsfoot trefoil hay and sweetclover green manure. Several previous reports have shown lower scab severity following alfalfa (eg. Wheeler, 1946). Except for potatoes following red clover hay, severe scab ranged from 10 to 19%.

Table 3.2. Influence of 1987 rotation crop on incidence of severe potato scab and black scurf, and on specific gravity of subsequent (1988) potato crop at the Michigan State University Montcalm Research Farm in Entrican, MI.

1987 Crop	Tubers with Severe Scab†	Plots with Black Scurf	Tubers with Growth Cracks	Specific Gravity
	------------------	%	------------------	
Alfalfa GM‡	11.9b	6.3b§	5.0	1.080
Alfalfa Hay	13.8ab	8.3b	6.3	1.083
Red Clover GM	14.4ab	18.8b	6.9	1.083
Red Clover Hay	28.1a	18.8b	3.1	1.083
Birdsfoot Trefoil GM	16.3ab	8.3b	6.3	1.081
Birdsfoot Trefoil Hay	10.0b	25.0b	1.3	1.082
Sweetclover	10.0b	12.5b	9.4	1.082
Hairy Vetch	16.8ab	62.5a	11.9	1.081
Corn	18.8ab	18.8b	4.4	1.082
Prob.>F	0.09	0.0005	NS	NS

† Scab lesions on more than 25% of tuber surface area.

‡ GM = Green Manure, not harvested during the seeding year.

§ Means with the same letter in each column are not statistically different at 0.10 level using Duncan's Multiple Range Test.

Severe scab decreased linearly ($P=0.012$), from 21.6 to 8.8% of 'A' grade tubers, as N fertilizer rate increased from 0 to 225 kg ha^{-1}, suggesting that increasing rates of NH_4NO_3 reduced soil pH to levels inhibitory to *S. scabies* (Figure 3.1A). This inhibitory effect of N fertilizer was observed for all rotation crops. Blodgett (1940) also found that scab severity was reduced if N was applied to potatoes. Lapwood & Dyson (1966) used non-ammonium based N fertilizers at rates similar to those used in this study, and observed that scab increased with N rate, suggesting that the increase in scab was a result of delayed tuber initiation at higher N rates.

It has also been suspected that high NH_4^+ levels in the soil, from N fertilizer, may directly inhibit *S. scabies*. Because ammonium nitrate was used as the N fertilizer source in this research, this may be a factor in decreased scab. However, several observation suggest that the N status of the growing potato plant and possibly reduced soil pH, not the N form in the soil, influenced scab severity. First, potatoes without N fertilizer following most rotation crops were clearly N deficient by mid-July, 1988. And second, soil samples taken from selected rotations at this time contained extremely low or no detectable NH_4^+ to a depth of 1.2 m, regardless of N rate (data not shown). Previous reports also support the use of ammonium-based N fertilizers in soil acidification to control *S. scabies*.

The incidence of black scurf was also influenced by the crop preceding potato (Table 3.2). The percentage of plots with black scurf was generally between 6 and 25%. However, almost 63% of the potato plots following hairy vetch exhibited black scurf symptoms. Since *R. solani*, which causes black scurf, is known to be strongly affected by residue composition, the low C/N ratio of hairy vetch (approximately 12) may have allowed survival until infection could occur. Black scurf increased as N rate increased to 150 kg ha^{-1} ($P=0.001$; Figure 3.1B), when averaged across all rotations. As shown by many researchers (Wright, 1941;

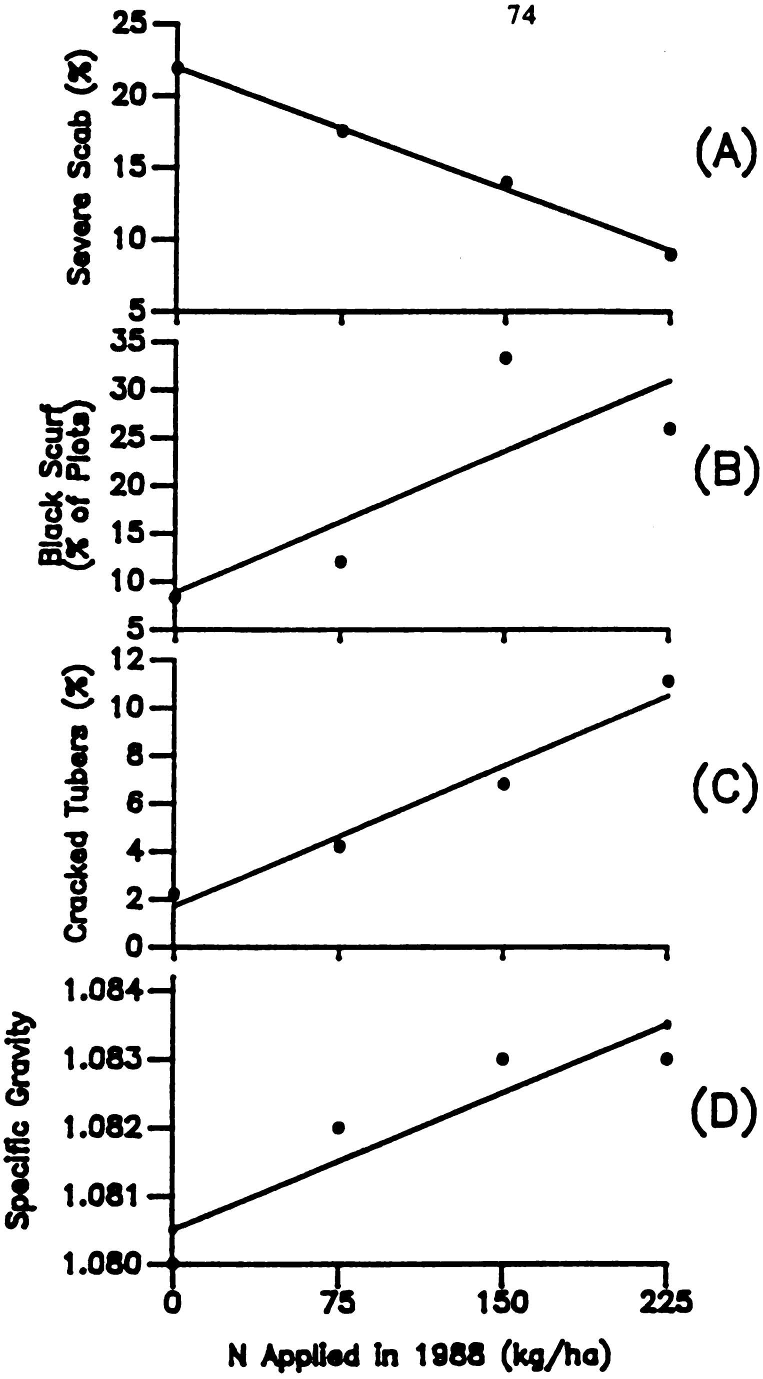

Figure 3.1. Effect of fertilizer N rate on (A) severe scab, (B) black scurf, (C) growth cracking, and (D) specific gravity of 'A' grade tubers at Montcalm. Regression equations for A, B, C, and D, respectively: Y=21.94-0.057N, R^2=0.99; Y=8.76+0.099N, R^2=0.67; Y=1.68+0.039N, R^2=0.97; and Y=1.0805+0.0000133N, R^2=0.87, where Y=response and N=fertilizer N applied (kg ha^{-1}).

Davey and Papavizas, 1959, 1963), *R. solani* infection of many plant species increases when exogenous N is applied, primarily due to the increased saprophytic ability of *R. solani* when adequate soil N was available.

Tuber quality parameters not directly influenced by soil-borne pathogens, like growth cracking and specific gravity, were not affected by previous rotation crop (Table 3.2). Growth cracking of tubers, generally caused by moisture or nutrient conditions that promote rapid tuber bulking, increased linearly ($P<0.001$) as N fertilizer rate increased to 225 kg ha^{-1} (Figure 3.1C). When no N fertilizer was applied, 2.2% of tubers exhibited noticeable cracks, while 10.8% of tubers were cracked when 225 kg N ha^{-1} was applied. Specific gravity also increased linearly ($P=0.045$), from 1.080 to 1.083, as N rate increased from 0 to 150 kg ha^{-1} (Figure 3.1D).

CONCLUSION

Although considerable research has examined the effect of individual pathogens on potato yield and tuber quality, production of potato is usually affected by multiple pathogens simultaneously. For this reason, it is valuable to examine the relative efficiency of different rotation crops in increasing or decreasing pathogen populations or disease severity. Table 3.3 summarizes the relative population of *P. penetrans* (November, 1987 sampling), and severity of scab and black scurf, each of which was significantly affected by rotation crop. Ranking is based on differences shown by Duncan's Multiple Range Test (Tables 3.1 and 3.2), with the lowest ranking in each category having the lowest pathogen population or disease severity.

The sum of individual rankings provides an indication of the general suitability of different rotation crops for disease prevention in potato production. None of the rotations examined is expected to completely control disease problems if

Table 3.3. Ranking of rotation crops based on population of root-lesion nematode (November, 1987), and severity of common potato scab and black scurf at the Michigan State University Montcalm Research Farm in Entrican, MI.

1987 Crop	Root-Lesion Nematode	Potato Scab	Black Scurf	Ranking Sum
	---------- Ranking ----------			
Alfalfa GM	1.5†	1.0	1.0	3.5
Alfalfa Hay	1.5	1.5	1.0	4.0
Red Clover GM	2.0	1.5	1.0	4.5
Red Clover Hay	3.0	2.0	1.0	6.0
Birdsfoot Trefoil GM	2.5	1.5	1.0	5.0
Birdsfoot Trefoil Hay	2.5	1.0	1.0	4.5
Sweetclover	1.5	1.0	1.0	3.5
Hairy Vetch	4.0	1.5	2.0	7.5
Corn	1.0	1.5	1.0	3.5

† Ranking based on Duncan's Multiple Range Test; within each column, rankings more than 1.0 units apart are significantly different at 0.10 level of probability.

used as the sole management strategy. Alfalfa (as green manure or hay), sweetclover, and corn were equally beneficial (ie. lower sum ranking) in rotations, with similar sum rankings of 3.5 to 4.0. Red clover and hairy vetch, both as green manure, had the highest sum rankings and tended to significantly increase all disease parameters examined, and thus would not be recommended if disease problems were evident. The other rotations, which had similar sum rankings, did not profoundly affect any parameter. With these rotations, neither pathogen control nor increased disease severity would be expected.

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