POTATO NUTRITIONAL MANAGEMENT CHANGES AND CHALLENGES INTO THE NEXT CENTURY

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Abstract

Plant nutrients are important components of the intensive production system used for potatoes. Nutrient management practices need to be improved for sustained and increased productivity. Better mangement decisions will be made when accurate information is available about (a) crop residues and rotation effects on nutrient cycling, (b) the nutritional characteristics and requirements of each variety, (c) bioavailability of nutrients in soils, and (d) fertilization and tillage effects on nutrient-use efficiencies. Plant growth and nutrient uptake responses to different nutrient availabilities must also be understood to maximize growth and nutrient efficiencies. Diagnostic management techniques for nutrients need to be related to fundamental chemical and biological processes in the soil and plant system to be applicable to different environments. This information can then be packaged with other knowledge into a comprehensive crop management system. These changes should bring our agronomic practices into better harmony with the natural processes of the production system, and yet be responsive to social and environmental concerns, and economic reality.

Introduction

Potato (*Solanum tuberosum*) nutritional management practices during the last 75 years have significantly changed in some respects but not others. Whitney (34) summarized 1769 tests conducted between 1869 and 1907 with 34 different fertilizer materials in 23 states. This report indicated that (a) two or three elements accounted for the largest share of yield increases, (b) fertilizer application rates were not always significant, (c) the fertilizer response was the largest on the more productive soils, and (d) that fertilizer applications on potatoes were profitable. A wide range of inorganic fertilizers and organic N sources were evaluated. In 1925 (1), the committee on soils and cultural research reported at the 12th Annual Meeting of the Potato Association of America that crop rotations, green manures, fertilizer ratios and sources, application methods, and fertilizer effects on tuber quality were being studied (1). Over the years, research activities moved from uniform fertilizer applications to selecting the best fertilizer source and rate

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for the soil. Soil testing as a basis for fertilizer applications, plant analysis to determine nutritional status, foliar feeding, fertigation, and specialized fertilizer application methods are activities of many research projects today.

Kunkel and Thornton (17) listed 18 variables influencing potato yields and quality (Table 1). We have added crop rotation to their list. Seven of these variables determine the yield potential, while ten are under the grower's control and determine actual yields. Soil temperature and pests are partially controlled by the grower. Most either directly or indirectly affect the nutritional management of the potato crop. Those variables that have a major influence on the grower's nutritional management are soil type and temperature, variety, seed quality, plant populations, crop rotation, nutrients, days grown, and timeliness of operations. Future needs or changes in these areas will be important for sustained and increased productivity. The objective of this paper is to identify where research is needed to improve our nutritional management practices for potatoes.

Cultural Management

Green manures, particularly legumes, were extensively used in past farming practices as main sources of plant available N. Recent emphasis on low-input sustainable agriculture has renewed interest in using crop residues as nutrient sources for other crops. The previous crop can have a very significant effect on nutrient uptake by potatoes (Table 2). These differences are not always correlated with preplant soil test concentrations. Another precropping effect was shown in a recent study where a precrop of corn (*Zea mays*) had more effect on Zn uptake by beans (*Phaseolus vulargis*, L.) than applying 11 kg Zn/ha (18). Different degrees of this effect also occurred in sweet corn and potatoes. Nutrient cycling from the precrop residues and vesicular-arbuscular mycorrhiza (VAM) infection of the bean test crop were identified as the principal mechanisms responsible for this effect (11). Potatoes are considered to be non-VAM plants compared with other crops (13).

The use of cover crops and crop rotation practices may also have other major effects upon crop management. A wide variety of green manure treatments suppressed potato early dying caused by *Verticillium dahliae* Kleb in a recent field study (Table 3). Sudangrass (*Sorghum vulgare*) or corn was particularly effective as a green manure treatment in reducing the incidence of wilt and colonization by *V. dahliae*. The crop preceding potatoes sometimes has a greater effect on crop management than the length of the rotation (30). There is very little known about the effects of these practices on either the ecology of soilborne pathogens or upon nutrient availability as related to pathogenic symptom expression and plant nutritional needs. It is becoming increasingly apparent that we need to better understand these systems to gain their fullest potential. This information will become more important as pesticides now used for disease control are withdrawn.

TABLE 1.—*Production variables affecting tuber yield and quality. (Kunkel and Thornton, 1986).*

Not grower controlled, potential yield:

1. Frost free growing season
2. Day length
3. Light intensity
4. Air temperature
5. Wind
6. Humidity
7. Soil type

Partially controlled, actual yield:

8. Soil temperature
9. Pests (weeds, insects, diseases)

Grower controlled, actual yield:

10. Variety
11. Seed quality
12. Seed piece size
13. Number of plants/area
14. Moisture supply
15. Mineral nutrients
16. Soil compaction
17. Days grown
18. Timeliness of operations
19. Crop rotation*

*Added by authors.

TABLE 2.—*Effect of two years of green mature treatments on final nutrient uptake by Russet Burbank potatoes. (unpublished data, Westermann, D.T., 1990).*

	Green Manure Treatment**					
Nutrient	Fallow	Oats	Rye	Sudan-grass	Corn	Treatment Prob.
						(P > F)
N, kg ha^{-1}	133	180	144	177	156	0.0006
P, kg ha^{-1}	11	14	12	16	14	0.0009
K, kg ha^{-1}	196	274	215	263	240	0.0121
Ca, kg ha^{-1}	76	87	77	79	80	0.0317
Mg, kg ha^{-1}	36	49	42	52	47	0.0006
S, kg ha^{-1}	10	13	11	13	13	0.0023
Cl, kg ha^{-1}	30	41	28	49	44	0.0009
Zn, g ha^{-1}	75	100	88	105	93	0.0008
Cu, g ha^{-1}	33	49	37	50	48	0.0033
Mn*, g ha^{-1}	401	399	417	366	386	0.8419
Fe*, g ha^{-1}	1389	1104	1252	1080	1272	0.9843

*Problems with element contamination of plant materials.

**All treatments received a uniform fertilizer application.

Soil organic C or organic matter concentrations can be higher in rotations compared with monoculture systems. The importance of soil organic matter on corn productivity in Michigan is shown in Fig. 1 (21). Some of the increased productivity is from greater nutrient cycling from the crop

TABLE 3.—*Verticillium wilt incidence in Russet Burbank potatoes following two consecutive years of green manure treatments. (Davis,* et al., *1991).*

	Observation dates	
	27 Aug 1990	5 Sept 1990
Green manure crop	% apical stems infected* (upper 7.5 cm)	
Fallow	76 A	92 X
Oats	30 BC	47 YZ
Rye	40 B	59 Y
Sundangrass	16 D	38 Z
Corn	21 CD	40 Z

*Different letters within a date are significantly different at $p<0.05$, Duncan's Multiple Range Test.

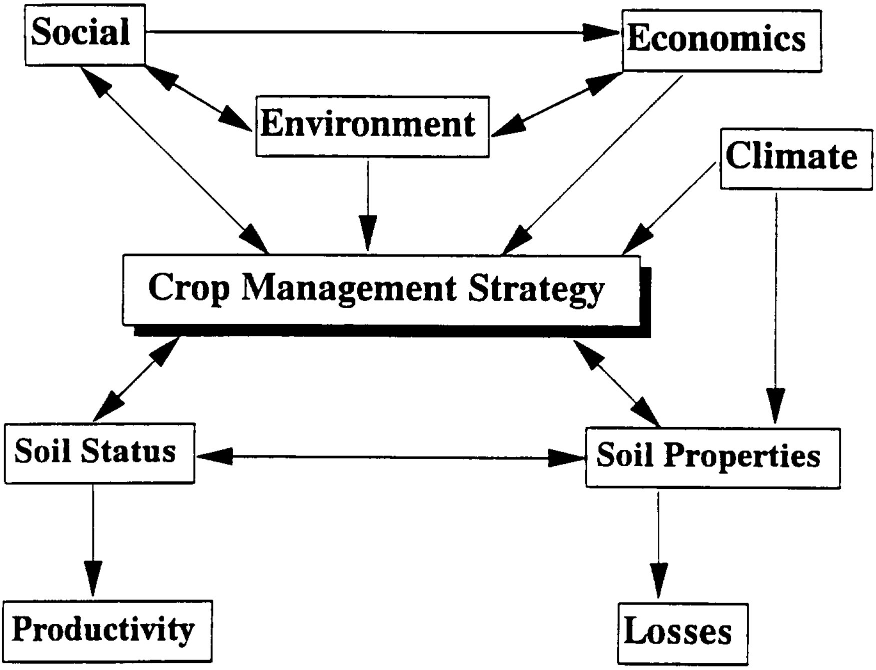

FIG. 3. Factors affecting the management strategy of agricultural systems (Adapted from Cole, et al., 1987).

residues and improved soil physical conditions, *i.e.*, soil tilth, aeration, etc. Increased crop residues can also reduce soil erosion losses.

Many of the essential nutrients influence disease incidence or severity (10). An adequate plant nutritional program helps suppress the development of many diseases and yield losses (15, 6). Balanced applications of N, P and K help reduce potato early dying and early blight. Heavy applications of N can stimulate excessive vegetative growth and development of an extensive foliar canopy. This may create a moist microclimate underneath the canopy and promote the development of aerial blackleg or *Sclerotinia* stalk rot, and tuber diseases associated with wet soils (*e.g.*, pink rot and leak).

Varietal characteristics will eventually be used as a basis for use in specific growing conditions. Plant nitritionists and physiologists need to work in cooperation with plant breeders to identify causative factors between varieties with different nutrient uptake and utilization characteristics. For example, root surface area and length was more important than root weight for N acquisition in two varieties (25). Root morphology is also important where diffusion is the main process of nutrient movement to the roots. Root hair length is particularly important in P and K uptake (29). Optimum N fertilization-management practices also need to be identified for each variety (20), showed that the N requirement for two new varieties was 80 to 90% of that needed for Russet Burbank. Relatively high soil NO_3-N concentrations at planting and tuber initiation tend to delay the start of linear potato tuber growth 7 to 10 days for indeterminant varieties but not for determinants (16). Significantly different N-use efficiencies, as measured by total N uptake, existed between the same varieties.

Total nutrient uptake is dependent upon the nutrient concentration in the tubers and their growth rate, the duration of tuber growth, and the amount in the tops and roots. An optimum plant top and root size (weight) will probably contain about the same amount of nutrients for a range of tuber yields. Fertilization rate differences then largely depend upon final tuber yields. However, a wide range of total nutrient uptakes are reported for the same tuber yields. This occurs, in part, because luxury uptake usually takes place where nutrient availability is not limiting.

Fertigation is an accepted practice, especially with sprinkler irrigation systems. This practice allows the grower to apply part of the anticipated total nutrient requirement preplant and to then adjust the nutritional regime upward to actual crop need during tuber growth. Fertilizer-use efficiencies are generally improved by applications closer to the time of actual plant need. Nitrogen is particularly adapted to the fertigation technique. Nitrogen use efficiencies were approximately 60% and 80% when applied preplant and during tuber growth, respectively (33). Applications using this technique depend upon the nutritional status of the plant, the interval between applications, the amount being applied, and projected tuber harvest dates. Daily nutrient uptake rates of tubers for selected varieties are shown in Table 4. Actual fertilization rates also have to account for efficiency factors and an additional amount to maintain the integrity of the tops and roots. An adequate N and P concentration for Russet Burbank tubers is about 1.55% N and 0.20% P on a dry matter basis. A tuber growth rate of 784 kg/ha/day at 21% dry matter would require 2.53 kg N and 0.32 kg P per day.

Fertilization placement practices also affect over-all use efficiencies. The relative efficacy of banded and broadcast applications depend upon the initial soil test concentration, the P fixing capacity of the soil, the crop to be grown, and the environmental conditions (9). Generally, banding increases the availability of those nutrients that can be "fixed" by soil components or leached out of the active root zone. Banding N at planting was generally more efficient than broadcasting before planting under furrow irrigation, but efficiency was reversed under sprinkler irrigation (Table 5). Phosphorus uptake and tuber yields were greater on a calcareous soil when the P fertilizer was either plowed-down or disked-in the seedbed before planting than where banded at planting (Table 6); however, the reverse may be true on neutral and acidic soils. Greater research efforts are needed to

TABLE 4.—*Tuber growth (fresh weight) and nutrient uptake rates of selected potato varieties during tuber growth.*

Variety	Average tuber growth rate (kg/ha-day)	Nutrient utilization (kg/ha-day)		
		Nitrogen	Phosphorus	Potassium
Russet Burbank				
	950[1]	2.8-4.0	0.41-0.60	3.1-4.0
	850[2]	2.4	0.65	3.3
Lemhi Russet	1000[1]	2.5-4.4	0.44-0.63	3.2-4.1
Centennial Russet				
	900[1]	2.8-4.0	0.39-0.56	2.9-3.8
Norgold Russet				
	1200[1]	3.0-4.5	0.53-0.75	3.9-5.0
Pioneer	1340[1]	3.5-5.5	0.59-0.85	4.4-5.6
Norchip	780[1]	2.0-3.1	0.35-0.49	2.6-3.2
Kennebec	1460[1]	3.7-5.8	0.64-0.92	4.7-6.2
Red McClure	1120[3]	3.8	0.56	3.7
Oromonte	1120[3]	3.4	0.45	3.8
White Rose	960[4]	3.2	0.39	5.0
Ave. of four varieties	900[5]	3.1	0.31	4.7

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TABLE 5.—*Effect of irrigation method and preplant N management on N uptake by Russet Burbank potatoes. (unpublished data, Westermann, D.T., 1990).*

		Irrigation Method			
N Placement	N-Serve*	Furrow		Sprinkler	
		········· kg N ha^{-1} ·········			
		7-13-89	9-1-89	7-13-89	9-1-89
Banded	–	130	214	138	240
	+	116	209	153	300
Broadcast	–	89	140	150	255
	+	136	216	199	231

*–/+ indicates without and with 1% a.i. nitrapyrin, respectively.
(Unpublished data, Westermann, D.T., 1990).

TABLE 6.—*Effect of P fertilizer placement on tuber yields and total plant P uptake by Russet Burbank potatoes on a calcareous Portnuef silt loam. (unpublished data, Westermann, D.T., 1976).*

	Yield			P Uptake		
P rate	Plowed down	Disked in	Banded	Plowed down	Disked in	Banded
kg ha^{-1}	····· t ha^{-1} ·····			··· kg P ha^{-1} ···		
0	(40.8)*	-	-	(11.7)*	-	-
34	52.0	46.5	43.7	15.4	17.2	13.4
134	53.0	54.9	49.4	24.3	22.0	14.5
336	54.8	-	-	29.5	-	-

*Control treatment.

develop methods that measure soil characteristics that will help to predict the most effective application method. Fertilizer materials that are available longer and undergo less fixation would also be beneficial.

Fertilization practices will also change with tillage practices. For example, conservation tillage will require that the immobile fertilizer materials be placed into the hill at planting or incorporated into the seedbed at some other time in the rotation. Development of restrictive layers from tillage operations may also prevent roots from having access to fertilizer-enriched soil zones. Likewise, deeper tillage may allow roots to explore larger soil volumes for available nutrients and reduce fertilization rates.

Variability in plant available nutrients in production fields can cause over-fertilization on some areas while others become deficient. Maximum production potentials are achieved when yields are not limited by available nutrients. We have known about soil variability problems for many years but significant progress is now being made in the development of variable fertilization systems (3, 12, 24). This should bring about some degree of uniformity and help the grower achieve maximum economic returns while minimizing environmental degradation problems and energy inputs for agricultural production.

Nutrient Diagnostic Tools

Soil tests are used to predict the need for a nutrient and the fertilization rate necessary for correction. These tests are usually based on empirical relationships as it is difficult, if not impossible, to duplicate the environment around the plant's roots. This process involves correlating the soil test concentration to plant nutrient uptake and yield, and then calibrating plant response to application rates at different soil test concentrations. This process works reasonably well but separate empirical relationships are often needed for different production environments.

Nutrient uptake is dependent upon the root characteristics of the plant and the supply characteristics of the soil. As the nutrient concentration at the soil-root interface is depleted, nutrients move to the root's surface from the surrounding soil solution by mass flow and diffusion processes. Soluble nutrients like Cl^-, SO_4-S and NO_3-N move by mass flow in the transpirational stream, while P and some of the micronutrients move to the roots by diffusion across a concentration gradient because of interactions with soil components. Soil factors influencing the nutrient concentration at the soil-root interface include the initial concentration in the soil solution (intensity), the capacity (buffering power) of the nutrient on the solid phase to replenish the soil solution, and its effective diffusion coefficient. Most soil tests adequately measure the intensity parameter but many fail to reflect changes in the soil's buffering capacity (14). Methods to better describe these processes under field conditions are needed before plant nutrition will be uniformly improved.

Mathematical modeling is making significant progress in relating the complex variables of soil, plant, and environment to nutrient uptake. Accounting for soil heterogeneity and root-growth characteristics are major problems relating models to field situations. In addition, microbial populations and their effects in the rhizosphere around the root are not considered in most models. Populations around the root can be 10-fold or larger than those in the surrounding soil in response to organic substrates from the roots (22).

Nearly all the N transformations in soil systems are affected by the microbiological population. These transformations include fixation (symbiotic and associative), mineralization, nitrification, immobilization and denitrification. Mineralization occurs when C-compounds containing N are used as substrates and the excess N excreted as NH_4-N. Nitrification is the biological oxidation of NH_4-N to NO_3-N. Denitrification occurs in anaerobic environments having a readily available energy source, particularly in waterlogged soils. Both NH_4-N and NO_3-N can be used by most plants, however relatively low concentrations of NH_4-N can be phytotoxic to potatoes compared with other agronomic plants.

The amount and the timing of N made available by mineralization is important for efficient N management. A total estimate is generally obtained from the soil's organic matter content but in some soils the N mineralized is not related to the organic matter content (4). To circumvent this problem the "potentially mineralizable N" was proposed. It is a laboratory estimate of the total N supplying capacity of a soil (26). This definable soil characteristic can be used in dynamic N simulation models to calculate the N mineralized during crop growth according to soil temperature and moisture (28). Better methods are needed for estimating this parameter. Presently, there is not a satisfactorily routine laboratory method to estimate the N made available by mineralization.

Some progress is being made to describe S and P cycles in soil systems (27). Little information is now available on cycling of other nutrients from organic residues for plant nutritional purposes.

The nutritional status of the plant is determined by analyzing plant materials. A plant part is generally selected for analysis since it is difficult to analyze the whole plant. The plant part must be responsive to nutritional changes in the plant and to nutrient availabilities. The fourth petiole or leaf-petiole down from the growing tip of potato plants is generally used for chemical analysis. Problems encountered include (a) selection of the correct petiole to sample, (b) changing nutrient concentrations with plant age, (c) recent fertilizer applications, and (d) varietal differences in "critical concentrations." Consistently sampling a younger or older petiole significantly changes the nutrient concentration without changing the general nutritional status of the plant (Table 7). These differences are caused by the mobility of various nutrients within the plant, and the balance between supply and utilization rates in various tissues. The upper stem, as an alternative to the petiole, eliminates the problem of petiole selection (31).

An empirical balance model using nutrient ratios is proposed as a solution to the problem of nutrient concentrations changing with plant growth stage (2). Critical nutrient ranges were also proposed (8). They are defined as the range between the nutrient concentrations at which we can reasonably expect no response and where the crop is deficient. These ranges would change for different growth stages. Another approach uses the dynamic ratio of the total nutrient uptake rate divided by the rate needed for tuber growth (32). Sufficient nutrient is available for growth when the ratio is greater than one. The nutrient, if sufficiently mobile, will be translocated from the vegetative portions of the plant to the tubers when the ratio is less than one. This ratio must then be related to the nutrient's concentration in a plant part for diagnostic purposes. Guidelines for using this technique for P during tuber growth are shown in Table 8.

Many past and present fertilization studies are conducted by applying different fertilizer rates and materials preplant, followed by measuring the final yields. The researcher may take a few plant samples during growth at some critical growth stage or some samples for total nutrient uptake. These data provide almost no information on nutrient flows within the plant during growth and development, nor do they help identify plant growth responses to available nutrient concentrations at different growth stages. Identifying the nutrient concentration-dry matter production relationship by which a plant reaches a particular yield will aid the development of effective and efficient nutrient management systems. This information will be increasingly more important in future management systems, particularly those utilizing dynamic soil-water-plant models.

Crop Management Systems

In most farming operations today decisions are being made about individual management factors largely independently of secondary factors. Increasingly, the production system is becoming more complex and addi-

TABLE 7.—*Effect of potato petiole position from the growing tip on selected nutrient concentrations in the petiole for the Russet Burbank variety.*

Petiole position	NO_3-N*	PO_4-P*	P	K	Zn	Mn
	mg kg^{-1}	mg kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}
2	12,000	1,860	3.4	86	54	25
3	14,600	1,690	3.3	96	40	23
4	15,150	1,640	3.2	106	30	24
5	18,500	1,250	2.6	110	24	24
6	18,200	1,030	2.2	112	20	27
7	19,000	970	2.1	106	18	28

*Soluble nutrient concentrations.

TABLE 8.—*The relationship between the total-P or soluble PO_4-P in the fourth petiole and the P-balance ratio (total plant P uptake rate:tuber P uptake rate) during tuber growth. (Westermann and Kleinkopf, 1985).*

Petiole Total P	Petiole Soluble PO_4-P	P Balance Ratio
%	%	
< 0.17	< 0.07	< 1
> 0.22	> 0.10	> 1

tional information is being added. The challenge is to develop a management tool that brings all the factors together into a total crop management system. A system in its simplest form is visualized in Fig. 2. This system can be divided into preplant and postplant segments for data input and output. Preplant input data includes variety selection, crop rotation and residue management, seed quality, tillage operations, soil properties (including soil tests for available nutrients, pH, texture, drainage, moisture, and water holding capacity), pests present, average climatic data for growing

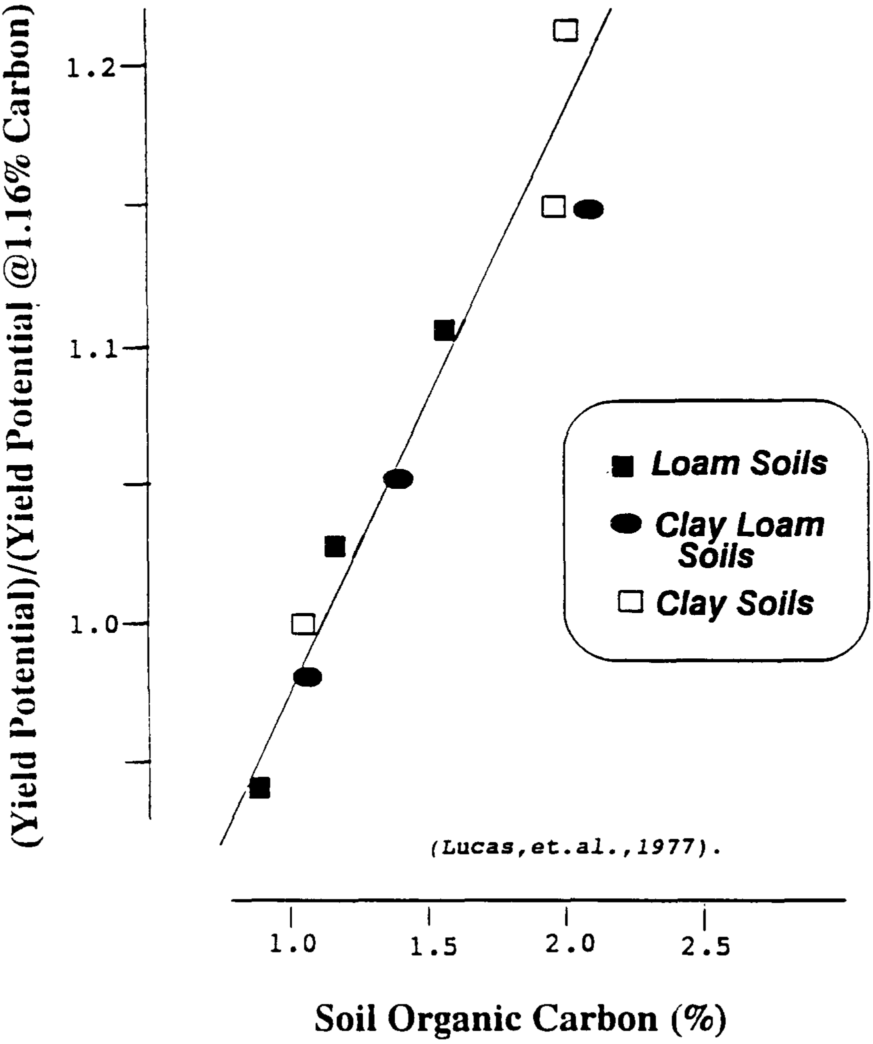

FIG. 1. Effects of soil C content on corn yield potential in Michigan (Lucas, et al., 1977).

season, harvest and market goals, production costs, and expected product value. Preplant output data for grower's use in making management decisions would be fertilizer recommendations and application methods, lime requirements, nutrients cycled from previous crop residues, planting date and seeding rates, seed inoculations, changes needed for optimum rhizosphere conditions, tillage needs, pesticide applications, irrigation needs, harvest date, and projected yields and profit. With this information growers would be in position for making the necessary decisions for managing their crop. The program may be rerun as many times as necessary for optimizing the system.

Additional postplant input data would be entered into the system once a crop is planted. This would include real-time on-site weather data, additional soil and plant tissue analysis, irrigations, actual plant populations, disease incidence and insect populations, and updated financial information. Postplant output data includes irrigation schedules, applications of pesticides, fertilizers and growth hormones, probable disease and insect population changes, and projected harvest date, with estimated tuber yields, quality, and profit. This would allow the grower to evaluate all the production factors and their interactions before making practical management decisions. Crop management systems are already being developed for some agronomic crops, *e.g.*, COMAX-GOSSYM and CALEX for cotton (19,23).

Overview

Agricultural productivity is affected by many factors but the general driving forces are climatic and economic. Management must integrate these forces within the constrainsts imposed by social concerns and issues, and environmental consideration (Fig. 3). The management strategy is also very dependent upon the properties of the soil, and the amount of available water and plant nutrients in the soil, soil pH and electrical conductivity (soluble salt content). These properties can also be enhanced or degraded through management practices. Even the harvestable product affects nutrient and crop residue removal. Other losses occur via erosion, leaching and gaseous processes, influencing the basic soil properties and thus, management. Management practices suitable for one production area may not be the best for all areas. The range of available nutritional-management options is also large, growing and becoming more complex. Fertilization rates that are not balanced with the other processes can have adverse effects on the environment and eventually, the soil's productivity. Future options for potato production will be affected even more than they are today by environmental and food quality concerns, energy costs and availability, and land suitability and availability.

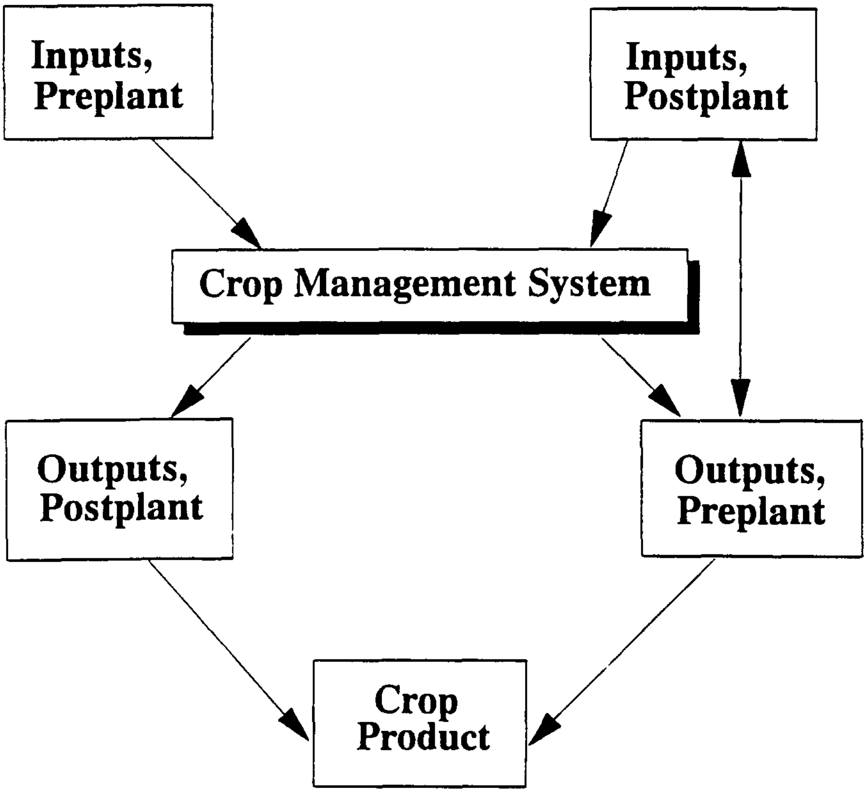

FIG. 2. Depiction of an interactive crop management system.

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