Using Systems Engineering and Reductionist Approaches to Design Integrated Farm Management Research Programs

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Systems research is needed to more effectively use information generated through reductionist approaches. One example is the need to develop integrated farm management systems that can be envisioned as a collection of agricultural management strategies that incorporate concerns of farmers, farm suppliers, environmentalists, the local community, consumers, and the general public. Our objective was to use systems engineering methods to design an integrated farm management systems research program that could ultimately develop integrated farm management plans. Systematic steps included: (i) defining the problem, (ii) identifying all factors potentially affected by any solution, (iii) developing concepts for solving the problem, and (iv) evaluating four feasible concepts by quantifying tradeoffs associated with each solution. Four approaches for designing an integrated farm management systems research program were developed and evaluated. They were establishment of ad hoc panels, awarding of grants, use of the existing Agricultural Research Service management structure, and writing of specific research contracts. The systems engineering process suggested that use of contracts would provide the best performance and that using ad hoc panels would be less desirable, primarily because they lacked financial incentives for the scientists and provided minimal control over actual research efforts. Because of minimal cost associated with initiating and operating ad hoc panels, however, the anticipated return per dollar invested was higher for that approach than for the three other concepts. In addition to designing an integrated farm management systems research program, this project also demonstrated how systems engineering can be used for planning complex agricultural research projects.

THE USDA Science and Education Office and EPA Office of Research and Development agreed to initiate an integrated farm management systems research program in 1991, with planned implementation for 1993. The research was to apply principles of integrated pest management and criteria for sustainable agriculture research programs, as outlined in the 1990 Farm Bill. The integrated farm management systems project was to complement the President's Initiative on Water Quality, with the first study to be implemented in the Walnut Creek Watershed, a management systems evaluation area near Ames, IA.

Integrated farm management systems are envisioned as a collection of agricultural management strategies that incorporate concerns of farmers, farm suppliers, environmentalists, the local community, consumers, and the general public. Protection of profitability for the farmer is to be balanced against diverse factors such as water quality, long-term sustainability, soil quality, air quality, or wildlife habitat.

We recognized that development of integrated farm management systems research would require a holistic, systems approach supported by mechanistic and component research traditionally conducted by reductionist scientists from both public and private sector research organizations. As stated by MacRae et al. (1989), the reductionist divides scientific problems into discrete and manageable pieces. In this way, scientists have been able to determine solutions to specific research problems, to identify cause and effect relationships, and to provide important scientific breakthroughs. Results from reductionist research generally provide answers to applied and fundamental questions that are documented through publication in technical journals. Research may be basic or applied, but it is usually organized along very narrow disciplinary lines. As a result, reductionist approaches can result in inconsistent and occasionally conflicting guidance when individual components are combined to solve complex agricultural problems. Inconsistencies can occur when the individual pieces of information are combined only to find that some relationships or interactions between relevant factors have been omitted or remain to be discovered (MacRae et al., 1989). This suggests that reductionist approaches should be used to help resolve specific problems that are identified through systems approaches, and that the component information should ultimately be integrated into holistic solutions.

Systems science, which is an engineering philosophy with its foundations in constructing models (both conceptual and mathematical), can be used to evaluate and optimize existing systems and-to design new systems (Bird et al., 1990). It has been used to design pest management programs with increasing frequency during the past 15 yr, and probably will play an important role in the development of future technologies such as integrated farm management systems.

The need to develop systems-research programs was identified as an important focus for Agricultural Research Service scientists in their most recent 6-yr plan (USDA, 1991). This type of research would require agricultural and environmental scientists to consider the entire range of questions faced daily by farmers and ranchers. However, the best approach for planning and initiating integrated farm management systems research was unknown. Our objective was to use systems engineering methods (Sage, 1992; Wymore, 1993) to develop feasi-

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ble, conceptual designs for an integrated farm management systems research program that ultimately could develop integrated farm management plans. The steps which were followed to design this research management system included: (i) defining the problem, (ii) identifying all factors potentially affected by any solution, (iii) developing concepts for solving the problem, and (iv) evaluating feasible concepts by quantifying tradeoffs associated with each solution.

METHODOLOGY

Problem Definition

Input and output requirements for an integrated farm management systems research program (Fig. 1) were defined to accept laws and regulations that exist or may be developed to address concerns regarding the effects of agricultural practices on the environment and safety of the food supply. Site specific information, including factors such as farm size, types of equipment, etc., and needs of farmers who participate in an integrated farm management systems research program were also identified as critical input. Information on the enviornmental, economic, and social effects of current and past practices was identified as critical input, so that criteria for testing long-term effects of integrated farm management system designs could be specified and fine-tuned after implementation. Input of fiscal resources available for conducting integrated farm management systems research were also recognized as essential. The outputs were to include specific farm management strategies or plans and communication in various styles and formats including technical and non-technical publications, software, and other materials.

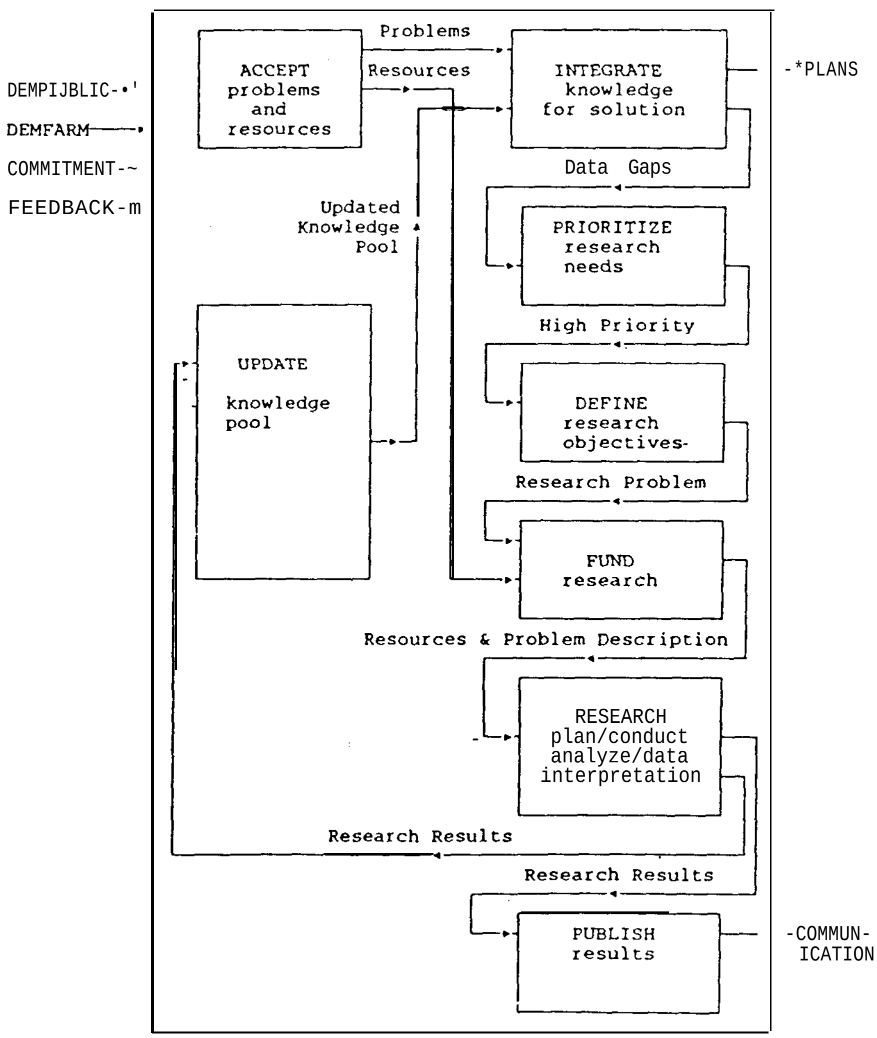

Fig. 1. **Functional diagram for designing an integrated farm management systems research program. Factors outside the rectangle are inputs to or outputs from the overall system lo be designed. Input abbreviations are defined as: DEMPUBLIC-multi-faclor demands by the public for a clean environment, viable rural communities, and safe food; DEMFAHM-multi-factor requests by farmers for management information; COMMITMENT-financial or other forms of commitment to the research program: FEEDBACK-multi-factor information regarding effects of farming practices in the Walnut Creek Watershed. Output abbreviations are defined as: PLANS-a set of alternative farm management plans; and COMMUNICATION--which consists of technical and non-technical research publications, software modules, decision-aids, etc.**

The primary customer for the integrated farm management systems design project was the Agricultural Research Service National Program Staff. Its input was used to set system boundaries (outer rectangle in Fig. 1). They requested that the integrated farm management systems research program help guide various research activities so that the results ultimately would be useful for designing integrated farm management plans for the Walnut Creek Watershed. They also requested that the project identify the criteria needed to evaluate the effectiveness of an integrated farm management systems research program. Additional information used to establish system boundaries and requirements was obtained by interviewing and gathering input from more than 150 people who represented farmers, scientists, sociologists, economists, the agrichemical industry, the Practical Farmers of Iowa, the Rodale Research Institute, and administrators from Agricultural Research Service, EPA, Cooperative States Research Service, Soil Conservation Service, and Extension Service (Table 1).

In addition to satisfying the performance requirements specified by these individuals, the integrated farm management systems program also had to fit into the existing research and management structure at the Walnut Creek Watershed. This included working with the management system evaluation area activities, and the EPA midwest agrichemical surface/subsurface transport and effects research program. These current research activities address field-scale water quality problems and include the participation of approximately 70 farmers in the watershed. Projects are approved by the director of the National Soil Tilth Lab in Ames and other principal investigators of the Iowa management systems evaluation area project. Projects are coordinated with respect to farmer participation, data collection, and compatibility with the geographic information system being developed and maintained at the National Soil Tilth lab. Implemented projects are monitored, data is archived in a uniform database, and eventually the information is distributed in various research and technology transfer publications.

Factors Affecting Integrated Farm Management Systems

Three categories of requirements were determined to be important for evaluation of an integrated farm management systems research program. These were: (i) how well the system operated, (ii) how well the resultant farm plans met the stated objectives, and (iii) how productive the system operated from research and administrative viewpoints. A three-tier organizational structure was used to organize these performance criteria (Table 2).

The integrated farm management systems research project also was directed to address some of the deficiencies existing at Walnut Creek. For example, (i) there were no activities in sustainable agriculture and integrated pest management efforts were operating only at the monitoring level, (ii) there was no identifiable mechanism for input from farmers with specific problems, (iii) data from EPA's monitoring program were not being used as feedback to improve the farming systems being evaluated, (iv) proposed projects were not prioritized in a consistent manner with respect to research gaps, (v) there was minimal effort to incorporate the social and economic factors, and (vi) specific databases for developing farm plans did not exist.

Table 1. Primary concerns of various groups who may be affected by development and adoption of integrated farm management systems.

Survey group	Primary concern
Farmers and ranchers	Provision of new farm or ranch management strategies that increase profit. reduce work or risk, or decrease time involvement.
Environmentalists	Improvement in or preservation of a clean and safe environment in terms of water quality. soil quality. air quality and habitat. Also, an improvement in assessment technology and reduction in non-point source pollution.
Sustainable agriculture	Development of long-term, productive agricultural systems that preserve or recycle soil and nutrient resources. Also, farming practices that result in a less stressful family environment and more stable community environment.
Research scientists	Development of research programs that identify and address critical knowledge gaps within integrated farm management systems technology and produce applicable results.
Extension personnel	Provision of alternative farm management strategies and development of decision aid systems that are relevant and reliable.

Concept Development

Conceptually, the integrated farm management systems research program is to function as shown in Fig. 1. Problems, ranging from a farmer's request for site-specific best management plans to information requests by the Soil Conservation Service and resources are provided as input to a subsystem responsible for overall project management. Resources including time, money, gifts-in-kind, etc., are directed to a subsystem that controls the funding of all activities. Requests for farm management plans are sent to a subsystem where the existing body of knowledge is evaluated. This process may be accomplished by a committee or with highly sophisticated decision support software. Outputs following evaluation of existing information include integrated farm management plans, either recommended or interim, and identification of information gaps that must be filled before a recommended plan can be generated. The information gaps are prioritized, clearly defined with respect to the type and quality of information which must be obtained, and funded for research. Research results are published and used to update the database used to formulate the farm plans.

Alternative concepts for actually developing an integrated farm management systems research program will vary. They will consist of different numbers of compo-

Table 2. Performance requirements, priorities (weight), and standard scoring functions (SSF) used to evaluate concepts for systems designed to create an integrated farm management systems research program that would produce farm plans and research information for the Walnut Creek Watershed near Ames, IA.

Level I	Level II	Level 111	Description7	Weight	SSF‡
System operation				0.30	
	Capacity		Number of farm management problems the system can handle at one time.	0.15	1
	Time delay		Length of time from when a problem is submitted until an acceptable solution is found.	0.15	14
	Flexibility		Ease with which the systen can handle new situations (i.e.. new crops, tillage practices).	0.10	5
	Unaddressed problems		The number of requests for which no acceptable plan can be formulated.	0.15	9
	Availability		Availability of system for processing inputs and creating outputs.	0.15	1
	Reliability		Reliability of system for processing inputs and creating outputs.	0.15	1
	Maintainability		Maintainability of system for processing inputs and creating ouputs.	0.15	1
Quality of farm plans				0.35	
	Environmental			0.40	
		Surface water quality	Measures of pesticides, nutrients, toxic substances, and sediment.	0.20	1
		Groundwater quality	Depth and levels of pesticides, nutrients. and toxic substances	0.20	1
		Soil quality	Organic matter, annual erosion, infiltration. acidity, salinity, plant rooting depth, microbial activity. and soil physical properties.	0.20	1
		Air quality	Odors, reduced visibility and volatilization of pesticides	0.15	1
		Habitat quality	Availability of food, corridors, wetlands, biodiversity. and farm impact on endangered or nontarget species.	0.15	1
		Nontarget pesticide impact	The potential to change the number of non-target species killed by pesticides.	0.10	1
	Social			0.20	
		Farm-worker safety	Accidents and illnesses attributable to farm practices.	0.50	8
		Food safety	Pesticide residues, mycotoxins, and foreign material present.	0.50	8
	Economic			0.40	
		Profit	Net farm income.	0.30	1
		Production	Yield or net productivity of farms.	0.10	1
		Pest costs	Costs of controlling pests or losses due to pests.	0.10	1
		Storage	Cost of maintaining excess structures or renting space if on-farm capacity is insufficient.	0.10	1
		Labor	Costs for owner-supplied and hired labor.	0.10	1
		Marketing	Costs of transporting farm products to primary markets.	0.10	1
Research productivity				0.35	
	Cooperation			0.20	
		ARS	Agricultural Research Service (ARS) support for integrated farm management systems research.	0.30	1
		EPA	EPA support for integrated farm management systems research.	0.20	1
		Public	Public (including university) support for integrated farm management systems research.	0.20	1
		Farmer	Local support for integrated farm management systems research.	0.20	1
		Industry	Agricultural industry support for integrated farm management systems research.	0.10	1
	Research completed			0.80	
		Publications	Number of technical and non-technical articles with information from the Walnut Creek Watershed.	0.60	13
		Software developed	Computer software packages developed to assist farmers and others with selection of integrated farm management systems plans.	0.20	13
		Identification of information gaps	Number of knowledge gaps identified by integrated farm management systems research programs on the Walnut Creek Watershed.	0.20	13

† Each parameter will be evaluated relative to existing conditions prior to developing or implementing an IFMS program on the Walnut Creek Watershed.
‡ SSF = Standard Scoring Function as defined by Wymore (1993); Weight-relative weight. priority, or importance with the requirement that within any grouping at any level. the values must add to 1.0.

nents and actually solve the problem of incorporating an integrated farm management systems research program into operations at the Walnut Creek Watershed in different ways. Since all system concepts must meet the same performance criteria, however, alternative designs can be compared based upon their anticipated performance and use of resources or cost. The process for evaluating the concepts is shown mathematically in Eq. [l].

OVERALL INTEGRATED FARM MANAGEMENT SYSTEMS PERFORMANCE RATING

$$(R) = q_{SO} \times (wt_{SO}) + q_{QP} \times (wt_{QP}) + q_{RP} \times (wt_{RP}) \quad [1]$$

where:

q_{SO} = Score for system operation
q_{QP} = Score for quality of farm plans
q_{RP} = Score for research productivity
wt = Relative weight or importance of each factor

Concept Evaluation

Prioritizing performance criteria can be difficult because of conflicting views among customer groups. Important factors to a farmer may not be very important to a research administrator, consumer, or user of outdoor recreational facilities. Tradeoffs among all important criteria become more difficult as the number of factors which must be satisfied increases. For example, in designing a research program to ultimately produce integrated farm management plans, it may be necessary to balance the potential number of quality farm plans generated against the potential number of quality research papers written. With respect to an individual farm plan, tradeoffs may have to be made between preventing pesticide contamination of tile-drainage or groundwater resources and maintaining high and profitable yield levels.

The systems engineering approach facilitates such diverse comparisons by requiring that each criterion or figure of merit be assigned a weight or priority, based on information gathered during the interview process. Concepts which fail to satisfy thresholds for these criteria are rejected. For this project, weights were established using responses to questionnaires distributed to leaders of the Agricultural Research Service, EPA, and Cooperative State Research Service. In some cases, values were assigned by the authors using a 'best guess' method based upon knowledge and assessments of the information de-

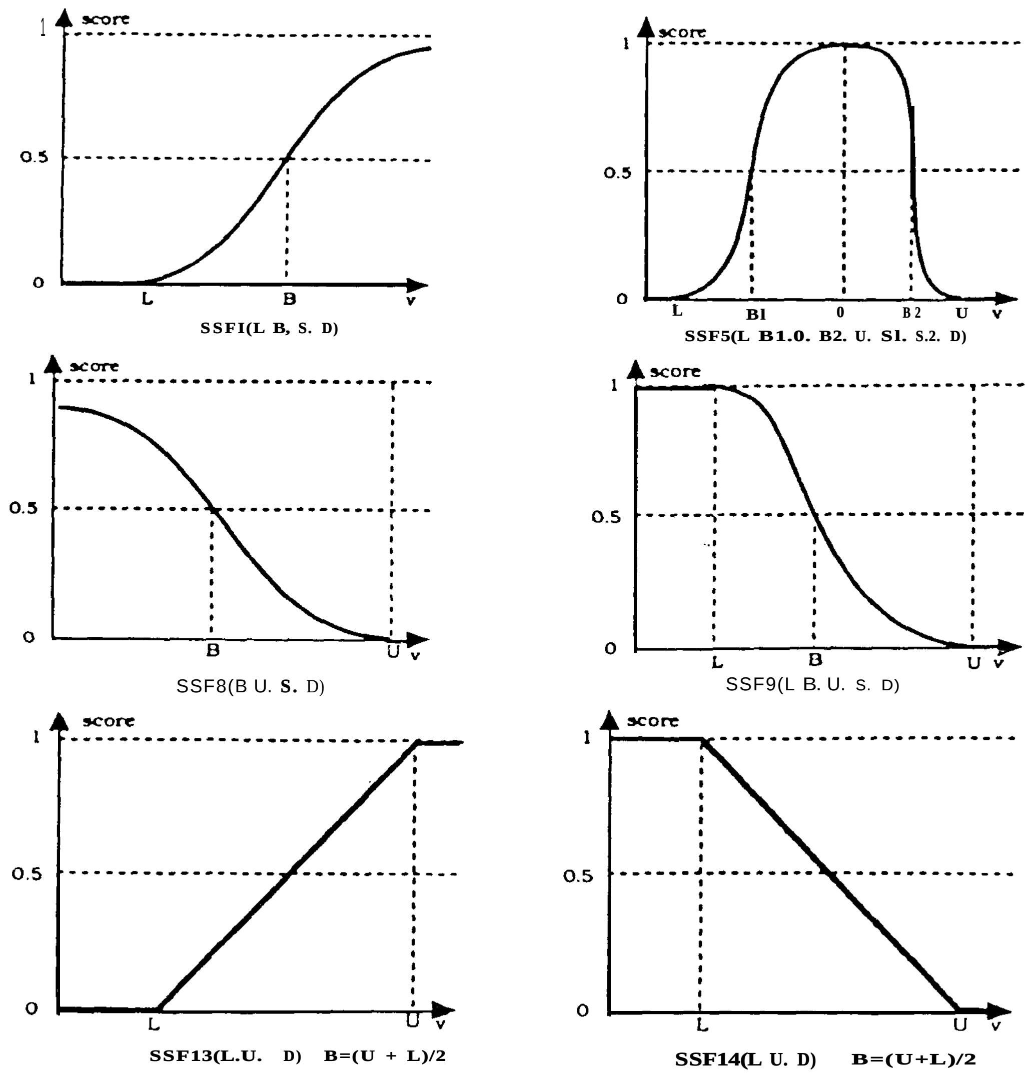

Fig. 2. Generic shapes for standard scoring functions (SSFxx) used to evaluate factors affecting the various concepts for designing an integrated farm management systems research program. (Adapted from Wymore, 1993.)

Table 3. Person or persons responsible for various system functions (as shown in Fig. 1) for each possible integrated farm management systems research program design concept that was evaluated. NSTL = National Soil Tilth Lab.

	Concepts for conducting integrated farm management systems research			
Functions	Panels	Grants	Existing management structure	Contracts
Accept problems	Director. NSTL	Director. NSTL	Systems scientist	Director. NSTL
Evaluate existing information	Ad hoc committee	Ad hoc committee	Systems scientist and information specialist	Systems scientist and information specialist
Prioritize research needs	Ad hoc comittee	Ad hoc committee	Systems scientist and ad hoc committee	Director. NSTL and ad hoc committee
Define research objectives	Ad hoc committee	Ad hoc committee	Systems scientist	Systems scientist
Control funding	Voluntary scientists	Ad hoc committee	Systems scientist and cooperators	Director. NSTL
Conduct research	Voluntary scientists	Principal investigators receiving grants	Systems scientist and cooperators	Systems scientist and person awarded contracts
Publish research results	Voluntary scientists	Principal investigators receiving grants	Systems scientist and cooperators	Systems scientist and persons awarded contracts
Update information database	Ad hoc committee	Ad hoc committee	Computer specialist and information specialist	Computer specialist and information specialist

rived through the numerous interviews with clients and customers.

Procedures for scoring each criterion must also be specified during the planning phase. To facilitate scoring, Wymore (1993) has developed 18 standard scoring functions that represent typical performance relationships. These scoring functions are used to normalize each criterion by assigning a value between 0 and 1 based on its performance compared with a target or baseline value. Performance at the target value receives a score of 0.5, better performance scores between 0.5 and 1 .0, and lower performance between 0.0 and 0.5. In addition to choosing the appropriate shape for each criterion, care must be taken to establish realistic upper and lower threshold, baseline, and slope values for each parameter. These values are developed using customer input or legislation for parameters such as pesticide concentrations in water resources. Generic shapes for standard scoring functions assigned to each performance requirement in Table 2 are shown in Fig. 2.

Four concepts for designing an integrated farm management systems research program were develpoed and evaluated. These were establishment of ad hoc panels, awarding of grants, use of existing Agricultural Research Service management structure, and writing of specific research contracts. Methods for fulfilling each critical function shown in Fig. 1 are described in Table 3.

Ad hoc panels require voluntary cooperation of personnel from the Agricultural Research Service, Iowa State University, and other organizations to develop and validate farm management plans for the Walnut Creek Watershed. This concept relies upon local and available scientific knowledge to deliver answers without creating, building or maintaining permanent database structures. The efficiency of ad hoc panels will depend primarily on the interest and schedules of committee members. No new funds are required, although “voluntary” participation diverts time and resources away from other areas and does incur a cost.

The grants concept uses public demands and farmer requests to set research priorities, develop grant guidelines or requests for proposals, evaluate new proposals and requests for continued funding, and award funding for new or continued grants. Grants operation (Table 3) would be similar to other USDA competitive grant programs, with the provision that it would be tailored to meet the specific needs of an integrated farm management systems research program in the Walnut Creek Watershed of central Iowa. The strength of using grants is the flexibility and relatively short-term commitment of resources that can be made to get specific answers. Its weakness is that even when requests for proposals are written with very specific requirements, they are still subject to individual interpretation and thus proposed activities may or may not meet needs for new knowledge that addresses the farmer requests or action agency problems.

The current Agricultural Research Service organizational structure would designate one or more research scientists who would be responsible for planning and overseeing field research programs, coordination and integration of the component research results, and determining how to incorporate the process- and systems-level information into a common database for all persons involved with research programs at the Walnut Creek Watershed. Their technical support would be responsible for developing and maintaining the database containing validated farm management options which could be accessible by decision support software to generate specific farm management plans. This concept requires a systems scientist who will have training and experience in integrated farming systems approaches, various agricultural disciplines, and, presumably, familiarity with the socio-economic aspects of farm management. The computerized database, once developed, would be expected to give quick, high quality responses to routine requests for farm plans. Performance of this concept would be limited by tradeoffs among time and resources that the research scientists would have to make while developing their research programs.

The contracts approach would require the development and maintenance of a database of existing, validated farm management systems for the Walnut Creek Watershed. To expand the database for new problems, research would be funded according to a prioritized list of problems resulting from new legislation, identification of critical research gaps, demands from consumers, or similar sources of input. Periodic review would assure the money is being used to perform the research agreed upon in the contract.

Table 4. Comparison of costs, overall performance, and value for alternative integrated farm management systems reserach program design concepts for the Walnut Creek Watershed in central Iowa.

Design concept	Set-up cost	Annual cost	Overall figure of merit	Value or score per thousand dollars invested
	s	s		
Ad hoc panels	0	6 000	0.1949	0.03248
Grants program	0	206 000	0.3269	0.00159
Current management system	35 000	391000	0.4332	0.00102
Contract research	35 000	391000	0.5255	0.00123

Primary components of contracts and their responsibilities are outlined in Table 3. The computerized database and decision support system is expected to provide quick, high quality responses to requests for solutions to farm management problems for which a solution already exists in the database. Targeted funding for those requests that require additional research should quickly fill the information gaps. One weakness may be resistance on the part of the researchers to accept the more structured contract approach to doing research. The panels, grants, current management approach, and contract methods for developing an integrated farm management systems research program were evaluated by constructing three hypothetical scenarios for a trade study (Wymore, 1993). The scenarios were: (i) status quo, (ii) environmental change, and (iii) marketing change. Status quo included little opportunity for new money and resources to be devoted to an integrated farm management systems research program. Environmental change assumed an important environmental problem was identified and resulted in a regulatory mandate prohibiting a-specific pesticide application or intense local concern. Marketing change assumed increased foreign demands for products with reduced pesticide residues or improved quality that might require changes in farm management practices. The latter were assumed to have a better chance of providing new or redirected resources for an integrated farm management systems research program.

It was not feasible to develop detailed models for the four concepts because of limited resources. Scoring functions and weights were therefore assigned to each performance criterion identified by the rough conceptual models. Based on performance, the contracts concept ranked highest with an overall score of 0.5255 on a scale of 0 to 1. The panels concept ranked lowest in performance, indicating that this concept probably would be the least effective of the four alternatives in producing the desired objectives of an integrated farm management systems research program.

The tradeoff between cost and performance was made simply by determining how much performance could be expected from each dollar spent for an integrated farm management systems research program. Total cost for each concept was based upon a one-time establishment expense plus estimated costs for 3 yr of operation (Table 4). This evaluation suggested that panels would give the most performance per dollar spent despite its low performance estimates. The risk of choosing this concept is that the degree of control is low and dependent upon local interests and competition with other priorities. From an administrative level, however, this type of approach may be looked upon as a fine-tuning of efforts within the current management systems evaluation area project on the Walnut Creek Watershed.

CONCLUSIONS

Our objective was to develop feasible concepts for establishing an integrated farm management systems research program for the Walnut Creek Watershed of central Iowa. The principles of systems engineering were applied and have been documented to show their application for planning complex agricultural research projects.

Four concepts (ad hoc panels, grants, the current management structure, and contracts) for developing an integrated farm management systems research program were identified and evaluated using three hypothetical scenarios. The systems engineering process suggested that contracts would perform best and that panels would perform poorly, primarily because they lacked financial incentives for the scientists and provided minimal control over actual research efforts. Because of minima1 cost associated with initiating or operating ad hoc panels, however, the anticipated return per dollar invested was higher than for the three other concepts.

This project also demonstrated how principles of systems engineering can be used for planning complex agricultural research projects. It showed that by determining all of the requirements for solving the problem during the planning phase, establishing how the information will be evaluated, and what questions must be answered, information generated by reductionist or component research can be more effectively combined and used to solve problems of concern to farmers, action agencies, environmentalists, or any other group.

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