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ABSTRACT

The Decision Support System for Agriculture (DSS4Ag) is an expert system being developed by the *Site-Specific Technologies for Agriculture* (SST4Ag) precision farming research project at the INEEL. DSS4Ag uses state-of-the-art artificial intelligence and computer science technologies to make spatially variable, site-specific, economically optimum decisions on fertilizer use. The DSS4Ag has an open architecture that allows for external input and addition of new requirements and integrates its results with existing agricultural systems' infrastructures. The DSS4Ag reflects a paradigm shift in the information revolution in agriculture that is precision farming. We depict this information revolution in agriculture as an historic trend in the agricultural decision-making process. Using this decision support system, in 1997 we generated a variable-rate fertilizer recommendation recipe for a 54.6 ha wheat field with the goal of optimum economic return, not maximum yield. The field was split into blocks, alternately fertilized with the variable-rate recipe and with the uniform application method used by the farmer. The DSS4Ag fertilizer recipe reduced fertilizer cost 39.7% and yield 3.3%, which resulted in a net economic gain of US $14.31/ha as compared to the uniform application used by the farmer. In 1998 the DSS4Ag was tested on a 64.7 ha wheat field and a 89 ha potato field. The DSS4Ag wheat recipe reduced fertilizer cost by US $15.81/ha, a saving of 30.6% between DSS4Ag and the recipe developed from recommendations by Kephart *et al.* (1991). The DSS4Ag potato recipe increased fertilizer cost by US $82.83/ha, a 70.1% cost increase compared to the conventional fertilization. Four test plots showed that the tested fertilizer management methodologies, while applying very different fertilizer rates, produced crops of similar yield and quality. The plots also demonstrated the DSS4Ag's ability to characterize and identify management zones of common and different productive potential.

INTRODUCTION

The notion of a paradigm shift to explain the scientific revolution that is precision agriculture has been discussed in the National Research Council report on precision agriculture in the 21st Century (1997). This was further emphasized at the 3rd International Conference on Precision Agriculture where 15 workgroups ranked the need for decision support systems the most important (Robert, 1996).

We depict this information revolution in agriculture, called precision agriculture or site-specific agriculture, as an historic trend in the agricultural decision-making process (Figure 1) (Hoskinson and Hess, 1997).

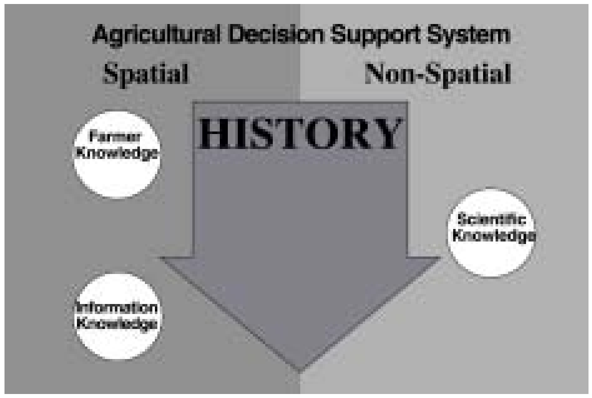

FIGURE 1. Historic trend in agricultural decision support.

First was the Farmer Knowledge system that made the decisions. Then, the Scientific Knowledge System developed in support of the Farmer Knowledge System. Now, the paradigm shift, the information revolution in agriculture, is what we refer to as the Information Knowledge System.

This new Information Knowledge System is now possible because of advances in technology such as the development of more powerful computers and the Global Positioning System (GPS) network of satellites, and the development of Geographic Information System (GIS) software. Another important development is the advances in artificial intelligence analysis, especially data mining methodologies.

Data mining, sometimes called Knowledge Discovery in Databases, has been defined as "The nontrivial extraction of implicit, previously unknown, and potentially useful information from data" (Frawley *et al.*, 1992). It uses machine learning, statistical, and visualization techniques to discover and present knowledge in a form that can be easily comprehended.

Adapting artificial intelligence information technologies to the needs of a practitioner-based industry like agriculture has produced a new and innovative toolset for precision agriculture management.

Our objective is to develop these tools, which must interface with the existing agriculture infrastructure and processes for making management decisions, by:

- Functioning with whatever frequency and spatial resolution of spatial data is available to an individual agriculture practitioner
- Accommodating external input of specifics from local experts (farmers, consultants, *etc*.) to make the decisions work for them
- Allowing the addition of new requirements and/or parameters on which to base decisions as defined by local experts and/or the scientific community
- Interfacing with existing hardware and software systems for site-specific characterization and management.

It is also our objective to take advantage of unique information technologies that solve the problem using as many of the growing environment variables as available, rather than limiting the solution to only a few limited possibilities in lookup tables and/or computer code. Also, our methodology does not have any crop specific limitations since the crop specific information is defined by the datasets, not our decision support system.

MATERIALS AND METHODS

Field studies on the effectiveness of artificial intelligence based technologies (*i.e.*, Decision Support System for Agriculture [DSS4Ag]) to develop effective site-specific fertilizer management strategies were tested on a potato and small grains rotational cropping system in Ashton, Idaho, USA from 1997 to 1998. The fields were irrigated by center pivot irrigation systems. The climate in the study area is very cold and moist from September through March. In spring it is wet and somewhat warmer. Summers are dry in most years, and temperatures range from below freezing to more than 32°C. The windiest periods of the year are spring and fall. The average annual precipitation is about 40cm to 56cm, and the average annual temperature is about 5.5°C. Elevation is about 1,615m. Soil characteristics are well-drained fine silty loams to silty clay loams on top of unweathered bedrock. Frost-free period is about 75 to 85 days, and cool temperatures restrict biological activity to only the summer months.

The DSS4Ag was used in 1997 to develop the optimum recipe for the variable-rate application of fertilizers on a 54.6 ha soft white wheat field. Analyses from grid soil sampling and site-specific yield data from a 1996 wheat crop in an adjacent field were used as the historic data input to this artificial intelligence based decision tool. The validation testing of the decision support system was based on a soil sample rate of approximately one sample per 1.62 ha, and a variable-rate fertilization recipe was generated on a 21.3m grid. Using a strip plot design, the entire field was divided into twelve treatment blocks. Six replicate blocks were managed using the DSS4Ag and six replicate blocks were managed with the conventional practices of the farm. At harvest, each block was harvested individually and the production measured.

In 1998, testing of the DSS4Ag continued with tests on an adjacent 64.7 ha soft white wheat field following a 1997 potato crop, and also on an 89 ha Russet Burbank potato field following a 1997 barley crop. On the wheat crop, DSS4Ag based fertilizer management was tested against a site-specific management recipe generated from guidelines developed by the University of Idaho (Kephart *et al*., 1991) for irrigated spring wheat in southern Idaho and a control of zero fertilizer input. On the potato crop, DSS4Ag based fertilizer management was tested against conventional uniform fertility management determined by the farm owners. A similar replicate block design with random assignment was again used in the 1998 tests. At harvest, each block was harvested individually and the production measured.

The 1998 tests also included four 45.7m by 18.3m embedded test plots, two in the wheat field and two in the potato field. Replicate treatments were arranged in a 3 by 3 Latin Square design within each plot. Treatments in the wheat plots compared DSS4Ag, university and zero fertilizer management strategies. Treatments in the potato plots compared DSS4Ag, the farm's and zero fertilizer management strategies. The embedded test plots were located in the fields within homogeneous management zones that represented the greatest divergence between management practices for the respective field, excepting one plot in the potato field that tested the divergence in DSS4Ag recipes. At harvest, each embedded test plot section was individually harvested manually and the production measured. Results were analyzed using the MIXED Procedure in the Statistical Analysis System (SAS) produced by SAS Institute of Cary, NC (The SAS System for Windows, release 6.12). Data from the two plots of the same crop were first analyzed separately, using a covariance model with treatment (DSS, university or farm, and zero) as a fixed effect. Data were then analyzed with plots of the same crop combined, and plot was added to the model as a fixed effect. Least square means and standard errors from the combined plot analyses are reported.

RESULTS

The field test of the DSS4Ag in 1997 was a successful demonstration of the methodology. The decision support methodologies reduced fertilizer input cost from US $85.34/ha to US $51.48/ha. This US $33.86/ha reduction represented a 39.7% cost saving using the DSS4Ag as compared to those blocks managed by conventional (the farm's traditional uniform applications) practices, with only a 3.3% decrease in yield (Figure 2). Economically, this use of DSS4Ag produced an actual US $14.31/ha benefit.

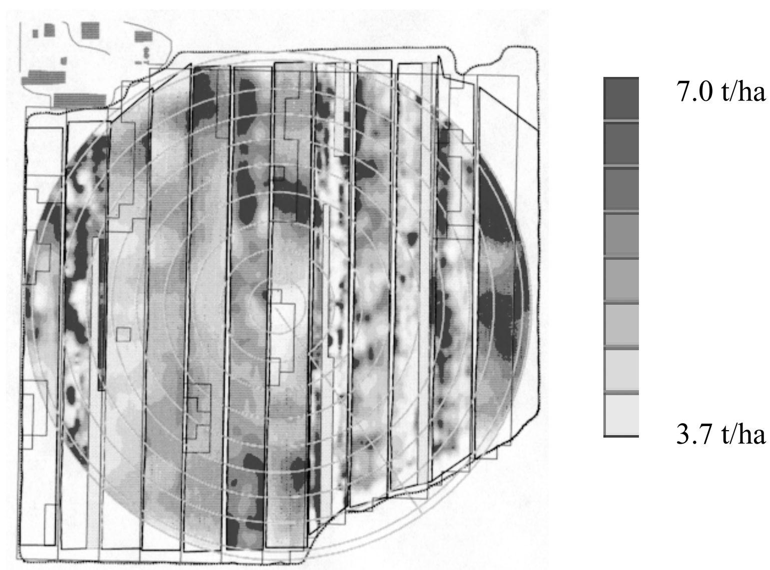

FIGURE 2. 1997 wheat yield map.

Notably, blocks managed with the decision support methodology had 18.1% less biomass than the blocks managed under conventional practices. This represents a Harvest Index (HI) of 0.60 in the conventionally managed blocks and 0.63 in the DSS4Ag managed blocks. This 0.03 difference could be thought of as a 5% increase in the crop's production efficiency.

The 1998 DSS4Ag wheat recipe repeated the success of 1997 by reducing fertilizer cost by US $15.81/ha, as compared with the other site-specific fertilizer management methodology based on university fertility guidelines (Kephart *et al.*, 1991). The reduced cost represented fertilizer savings of 30.6%, while average field-scale crop production was similar between the methodologies.

However, for the potatoes, the DSS4Ag recipe increased fertilizer cost by US $82.83/ha, a 70.1% cost increase as compared to the conventional fertilization, but the expected yield increase was not realized. Like in the grain, average field-scale crop production was similar between the fertilizer management methodologies.

The embedded plots tested the effectiveness of the different management methods under conditions that more effectively controlled the confounding effects of large-scale spatial variability. Across wheat plots, fertilizer application rate differences between the DSS4Ag and university methodologies were about 30%, just as in the field. For the DSS4Ag methodology, these differences represented approximately a 34% decrease in nitrogen, a 98% increase in sulfur, and a zinc application not included in the other methods. As expected, the grain and straw yield, and tiller count increased with the addition of fertilizer (Table 1). No differences in any measured crop parameter could be detected between the DSS4Ag and university guideline methodologies. The addition of fertilizer did not affect plant count. The different fertilizer management methodologies did not affect harvest index, test weight and protein content. However, for the separate plot analyses, distinct differences in these parameters were detected. As a result of the two plots residing in uniquely different management zones, both the DSS4Ag and university guideline methodologies applied higher absolute amounts of fertilizer on one plot over the other. The harvest index, test weight and protein were respectively 4.74%, 1.35% and 14.58% lower in that plot than the other, while straw yield was 18.6% higher.

TABLE 1. Combined-plots response of soft white spring wheat crop to site-specific fertilizer recommendation methodologies.

	LSmean±LSstderr			
	DSS	Univ.	Zero	F-value†
Grain Yield (t/ha)	2.28±0.07	2.39±0.07	1.60±0.07	33.43****
Straw Yield (t/ha)	0.76±0.04	0.83±0.04	0.49±0.04	17.34****
Harvest Index (%)	75.27±0.92	74.60±0.92	76.50±0.92	1.10
Test Weight (kg m^{-3})	812.25±3.06	809.41±3.06	809.67±3.06	0.26
Protein (%)	8.63±0.19	8.91±0.19	8.48±0.19	1.41
Plant Count (#/m)§	28±1	27±1	27±1	0.23
Tiller Count (#/m)§	81±3	80±3	56±3	17.80****

† F-value degrees of freedom for plant and tiller density = 66. For all other F-values, degrees of freedom = 30.

§ Plant and tiller counts are plants per meter within a row. Row spacing = 15.24 cm.

**** Significance at the 0.0001

In the potatoes, differences between conventional farm fertility management and DSS4Ag management were most notable in the application of potash. Conventional management practices uniformly applied 98 units/ha of potash, while site-specific DSS4Ag management ranged from conventional management potash levels to the maximum allowable application rates for the soil type of about 1,000 units/ha. Given the potential for such great divergence in the levels of recommended potash, one plot was selected in an area of greatest divergence between DSS4Ag and conventional practices. The other plot was selected in an area in which DSS4Ag potash levels were closer to the range of conventional practices. Irrespective of the fertilizer management methodology, all yield and quality productions parameters were significantly (p>0.001) different between the two plots, but the responses to the management methodologies were similar. In both plots, potato yield increased with the addition of fertilizer, but differences between the conventional and DSS4Ag methodologies were not detected (Table 2). Neither fertilizer management methodology made any significant improvements in the yield of packing or seed sized potatoes as compared to the yield produced by applying zero fertilizer. Interestingly, both fertilizer management strategies reduced the solids compared to the solids produced by zero fertilization. The higher fertility DSS4Ag methodology reduced solids by the greatest amount.

TABLE 2. Combined-plots response of Russet Burbank potato crop to site-specific fertilizer recommendation methodologies.

	LSmean±LSstderr			
	DSS	Farm	Zero	F-value†
Potato Yield (t/ha)	6.20±0.20	6.43±0.20	5.62±0.20	4.34*
Size >213g (t/ha)§	1.18±0.11	1.28±0.09	1.02±0.09	3.84
Size <213g (t/ha)‡	4.29±0.21	4.38±0.18	4.08±0.18	1.15
Solids (%)	21.50±0.04	22.10±0.04	23.70±0.04	12.92****

† F-value degrees of freedom for potato yield and specific gravity are 64 and 55 respectively. For all other F-values, degrees of freedom = 56.
§ Includes tubers of the size and quality for packing only
‡ Includes tubers of the size for seed only
*, **** Significance at the 0.02 and 0.0001 respectively

Both the 1998 DSS4Ag wheat recipe and the 1998 DSS4Ag potato recipe were generated from knowledge mined from historic data collected during the 1995 growing season, from the same fields and for the same crops as where the 1998 tests were done. Although the 1998 growing season accumulated almost 200 additional growing degree days by mid-September when the potatoes were harvested, both years had about the same number of growing degree days on July 1, by which time the plant populations were established (Figure 3). Spatially variable recipes can be affected by temporal

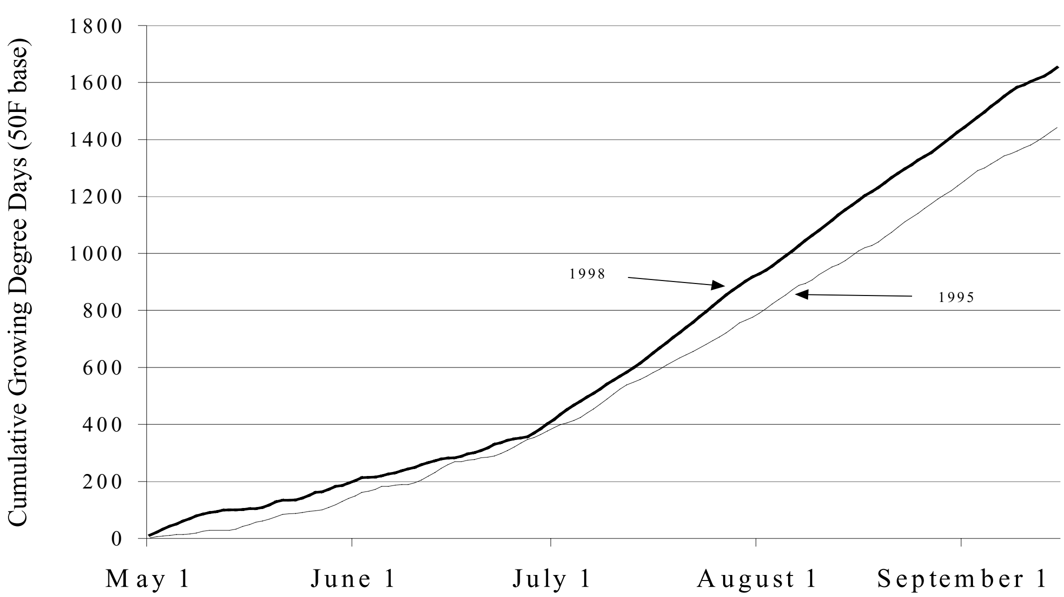

FIGURE 3. Comparison of 1995 and 1998 cumulative growing degree days.

differences in the historic growing environment from which the recipe was generated compared to the current environment in which the crop is grown.

DISCUSSION

Fertilizers are generally applied to crop fields at a uniform rate. These rates are based on a grower's experience and/or scientific research done by universities and industry. Guideline-based site-specific management uses these same general fertilizer rate recommendations and applies them to sub-field management zones rather than to the entire field. These well-proven fertility management methodologies were the basis for the farm's conventional and university guideline-based site-specific fertility management strategies against which the DSS4Ag methodologies were tested in this study.

The DSS4Ag defines two key pieces of technology:

1. A prototype expert system for site-specific management decision-making.
2. A partially automated decision support system architecture (Figure 4), that defines the interface between the decision-making tool, artificial intelligence information technologies and the existing agriculture infrastructure and process for making management decisions.

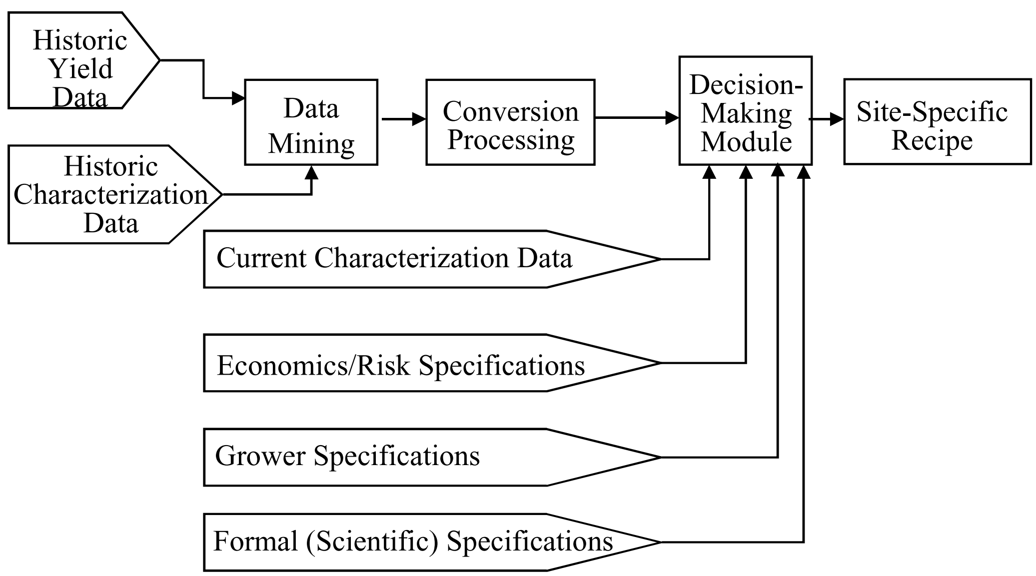

FIGURE 4. DSS4Ag architecture.

Unlike uniform conventional and guideline-based site-specific fertility management methodologies, our DSS4Ag methodology develops site-specific recommendations based on knowledge mined from historic data. This approach does not ignore, but builds upon the established scientific understanding of crop nutrition. Our approach includes collection of growing environment characterization data, and the use of that data with an artificial intelligence-based decision support system (*i.e.*, DSS4Ag). These decision support tools identify crop production success patterns in precision agriculture datasets, and use these patterns to make optimized site-specific decisions.

Two key ideas are at the foundation of the DSS4Ag approach:

1. Application of data mining technology to detect crop response patterns in site-specific agricultural datasets.
2. Re-casting these response patterns as mutually exclusive strategies in an optimization framework.

This works by constructing a historic spatial database containing information from previous growing seasons, for the crop to be fertilized. Typically, these data would be from the same field as the field for which the fertilizer recipe is to be generated, although if no historic data are available for that field, historic data from adjacent fields can be used as a starting point. Physical characteristics of the field, and soil fertility measurements taken after initial fertilizer application are included in the historic spatial database, as well as the resulting yield map constructed from real-time yield monitor data taken at harvest time. In a more advanced application of DSS4Ag, the yield function can be replaced by an enhanced function that might include additional factors such as crop quality or other special characteristics as well as just yield. This spatial database is then used as input to a data mining process.

The data mining process is based on a regression tree methodology, similar to those described by Breiman *et al.* (1984) and Kass (1980). The crop yield is the dependent variable in this process, with the soil fertility and physical characteristics as independent variables. The leaf nodes of the resulting regression tree are then considered as mutually exclusive strategies in an economic optimization context.

The leaf node characterization recipe statements are augmented with prior years' fertility data to render them suitable for recipe generation, rather than classification. The grower's expected market price and current fertilizer costs are then used in conjunction with the recipe statements and a spatial database of current soil fertility measurements to construct a recipe that seeks to maximize economic return to the grower. Appropriate scientific constraints (Scientific Knowledge System) are applied as part of the optimization process to ensure that the recipe is within realistic limits. Additional constraints can also be applied as required by the grower (Farmer Knowledge System). The resulting fertilization recipe is then converted into whatever specific machine-instruction input format is required by the commercial variable-rate fertilization application equipment to be used.

In the current study, this artificial intelligence-based DSS4Ag methodology as compared to conventional uniform fertility management practices resulted in significant fertilizer savings with only a slight reduction in grain yield in 1997. As an additional benefit, the total biomass of the crop was reduced, thereby reducing the straw residue that must be removed or tilled under. In 1998, we compared the site-specific DSS4Ag methodology to a university fertilizer guideline-based site-specific methodology. Again, the DSS4Ag produced the same quality and quantity of crop as the more commonly used site-specific management practice, but did so with a substantial savings in fertilizer input costs.

The 1998 wheat field test also included a management strategy of applying zero fertilizer to the crop. This test demonstrated a unique ability of our DSS4Ag methodology to discover site-specific management zones with uniquely different production potentials. For example, irrespective of differences in the absolute amounts of fertilizer applied by all tested fertility management methodologies, the uniquely different DSS4Ag located test plot sites never achieved similar production. While our DSS4Ag methodology was less successful at selecting appropriate (or economically optimum) fertilizer application rates for potatoes, it held true to its ability to define unique management zones.

We believe that the successes demonstrated to date using an artificial intelligence-based decision methodology can be primarily attributed to these tools' abilities to more effectively characterize a site's productive potential, and discover optimum management strategies within the historic record or existing knowledge base for achieving that potential. In contrast, it is our hypothesis that the less than optimum outcome experienced with the 1998 potato crop occurred as a result of a lack of enough historic characterization parameter(s) essential to Russet Burbank potato production. Russet Burbank potato production is very sensitive and responsive to temporal fertilizer management. As a result, regardless of our DSS4Ag methodology's ability to discovery unique management zones, spatial fertility management alone may often produce disappointing results because unpredictable temporal variation may negate spatial optimization.

CONCLUSIONS

These tests have demonstrated the integration of the farmer knowledge, scientific knowledge and historic knowledge in a way to effectively manage crop production. As more site-specific information becomes available, the data-mining system's ability to develop better and more appropriate site-specific, as well as temporal, response recommendations should also improve. We have recognized the value in applying these DSS4Ag methodologies to more accurately characterize unique field management zones, and have become increasingly more aware of the need to consider precision agriculture management in terms of managing spatial by temporal variability.

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