An Expert Advisory System for Wheat Disease Management

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An expert system for managing diseases of wheat that is both predictive and managerial has been developed for use in the Pacific Northwest (PNW) of the United States and is referred to by the acronym MoreCrop (Managerial Options for Reasonable Economical Control of Rusts and Other Pathogens). The acronym MoreCrop was selected because it describes the concept of how the system should be used. The purpose of MoreCrop is to present outcomes that may happen and give options for control, not to make specific recommendations. The user evaluates the information that is provided when certain environmental conditions and managerial practices are selected and, by a process of reasoning, determines the most economical control. MoreCrop was developed using the vast information available on wheat diseases together with tools from recent technological advances in the computer industry. Visual programming and object-oriented programming approaches made the system visually appealing, easy to use, flexible, extendable, and powerful.

MoreCrop was designed to provide various disease managerial options in different regions and agronomic zones of the PNW. It provides information, options, and suggestions to help the user make decisions regarding management of wheat diseases. It predicts diseases based on geographical regions, agronomic zones, crop managerial practices, cultivar characteristics, prevailing weather, and field and crop history. MoreCrop can also use past managerial decisions to reconstruct disease conditions, assist the user in reasoning which disease control option to select, and provide disease-related as well as cultivar-related information for teaching, research, and extension. The classical disease triangle is used as the overriding principle in predicting the diseases, i.e., a susceptible host, a virulent pathogen, and a favorable environment for disease development must exist for the disease to damage the crop. MoreCrop is a management system that evolved from earlier guidelines for integrated control of rusts and was later expanded to include other diseases of wheat. The management system is based on more than 30 yr of data on crop management, epidemiology, and disease control of wheat (11). Information from other plant pathologists and crop scientists was also utilized in developing the system (6–8,14,18).

The Managerial Environment

Geographical regions and agronomic zones of the PNW. The PNW is a region of great environmental diversity; it has the greatest diversity of environmental conditions in North America. Because of this diversity, most of the known wheat diseases occur in the PNW, and at least 16 disease groups have significantly limited yields. The occurrence and severity of diseases depend mostly on the geographical region, agronomic zone, crop managerial practices, susceptibility of wheat cultivars, prevailing weather conditions, and presence of virulent species, races, or strains of the pathogens. MoreCrop considers the environmental diversity of the PNW by giving a predictive disease output for the region and the agronomic zone where the wheat is grown. It is, therefore, important that the user of MoreCrop determines the correct region and zone where the wheat field is located.

North America can be divided into seven regions (Fig. 1) based on geographical barriers, prevailing winds and other weather factors, general crop management, and occurrence of specific stripe rust races (12,13). Region 1 comprises eastern Washington and Oregon, northern Idaho, and eastern British Columbia; region 2, western Montana and southern Alberta; region 3, southern Idaho and northern Utah; region 4, southwestern Washington, western Oregon, and northern California; region 5, northwestern Washington and western British Columbia; region 6, central California; and region 7, areas east of the Rocky Mountains. The current version of MoreCrop applies specifically to regions 1, 4, and 5, but other regions in North America have also been included for future expansion. Expansion of MoreCrop to wheat-growing areas east of the Rocky Mountains may require further division of region 7.

The five agronomic zones used in MoreCrop (Fig. 2) are a modification of

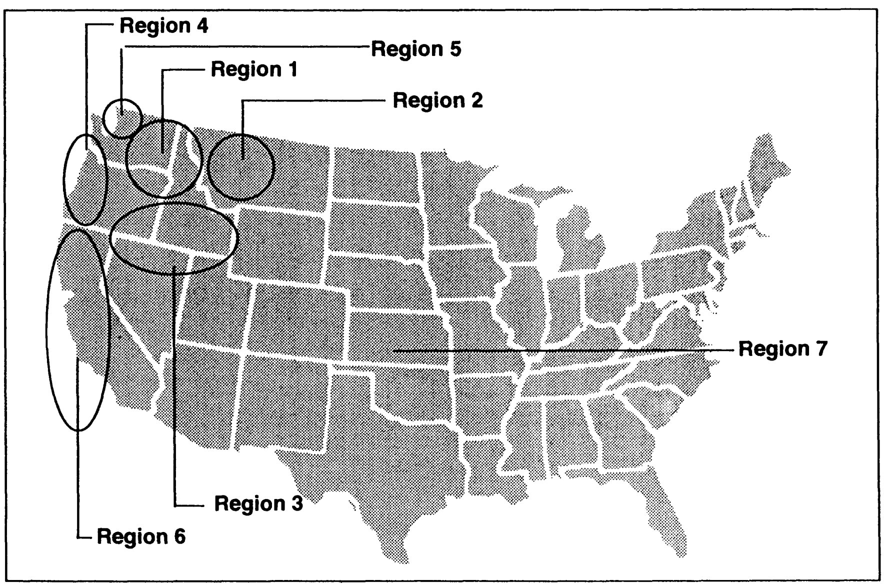

Fig. 1. Geographical regions of North America based on the distribution of stripe rust races, crop managerial practices, and other factors.

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the six dryland zones defined by Douglas et al (8). Two zones defined by Douglas et al were combined into zone 1, since the effect of weather on wheat diseases and the managerial methods are similar in those two zones. Douglas et al did not define zones for regions 4 and 5; therefore, zone 1 was also expanded to include those regions. The zones are described on the basis of four classes of annual precipitation, two soil depth regimes, and three categories of cumulative growing degree days (GDD). The four classes of annual precipitation are moist (>40 cm [>16 in.]), moderately dry (35–40 cm [14–16 in.]), dry (25–35 cm [10–14 in.]), and very dry (<25 cm [<10 in.]). The soil depths were deep (>100 cm [>40 in.]) and shallow (<100 cm [<40 in.]). The categories of cumulative GDD from 1 January to 31 May were cold (<700), cool (700–1,000), and hot (>1,000). Thus, zone 1 is defined as cool to cold and moist with either deep or shallow soil. Some areas of the zone have snow cover for extended periods. Precipitation is usually adequate to support a crop every year (annual cropping); summer fallow is not required. Zone 2 is defined as cool and moderately dry with deep soil. With a well-planned crop rotation and appropriate crop managerial practices, precipitation is adequate for annual cropping. In drier years, summer fallow may be necessary to conserve water, especially in the drier areas of the zone. Snow usually is not present for extended periods. Zone 3 is defined as cool and dry with shallow soil. Moderately low precipitation can recharge the shallow soil profile of this zone to support annual cropping; summer fallow is often of little advantage for water storage because of the shallow soil. Irrigation can be used to provide additional water. Zone 4 is defined as cool and dry with deep soil. Because annual precipitation usually is not sufficient to fill the soil profile, summer fallow in alternate years is necessary to have enough water to grow a crop. Supplemental irrigation can be used to provide additional water. Some areas of the zone may have extended snow cover. Zone 5 is defined as hot and very dry with either deep or shallow soil. Irrigation is usually necessary to produce a crop.

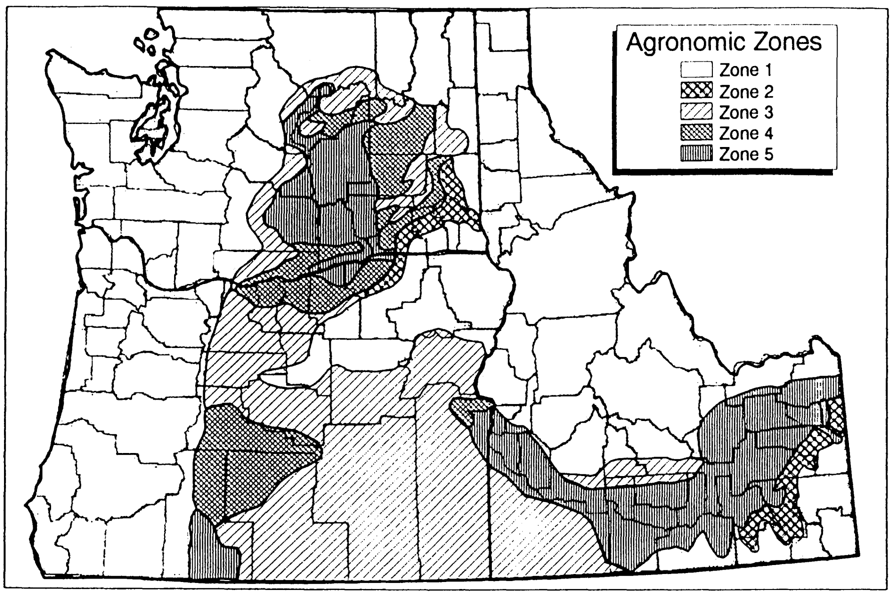

Fig. 2. Agronomic zones of the Pacific Northwest based on annual precipitation, soil depth, and growing degree days.

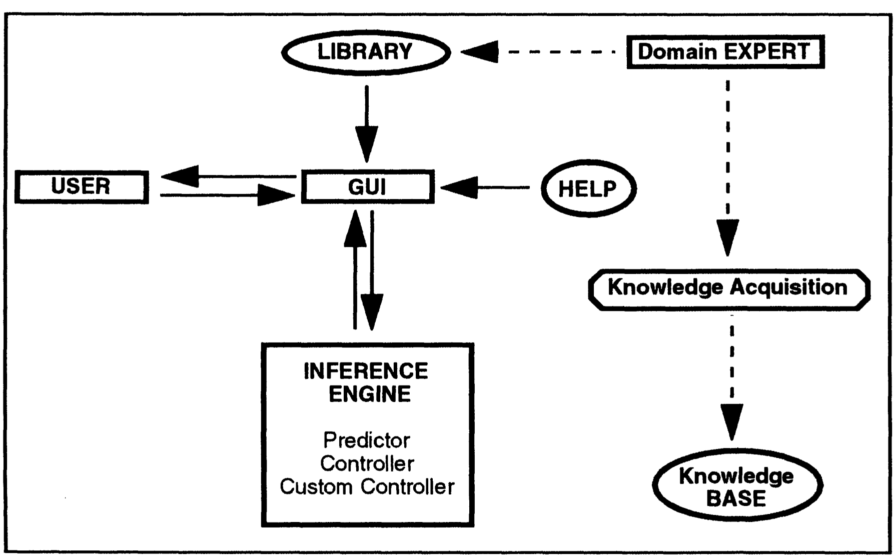

Fig. 3. Components of MoreCrop and their functional relationships. The solid single arrows and the double arrows signify a static linkage of information and a two-way interactive exchange of information. Dotted arrows signify the route for updating information in the library and rules in the knowledge base.

The weather conditions within each zone are further defined on the basis of the long-term historical records of temperature (cold, cool, warm, hot) and the kind and amount of precipitation (snow, wet, dry) that occur in early fall (late August to early October), late fall (late October to early December), winter (late December to early February), early spring (late February to late April), and late spring (early May to early July). The seasonal weather, which is based on 30 yr of historical records for each combination of region and zone, is used as the default setting. In situations when the weather in any season departs from normal, the weather setting can be changed to the one that best describes the prevailing condition.

Diseases of wheat in the PNW. Most of the wheat diseases in North America can be found in the PNW because of the diversity in environment and crop managerial practices. Sixteen disease groups are considered important in the PNW and are used in the system. The following is a synopsis of the wheat diseases that are important in the PNW.

Stripe rust, leaf rust, and stem rust—caused by *Puccinia striiformis* Westend., *P. recondita* Roberge. ex Desmaz., and *P. graminis* Pers.:Pers., respectively—are indigenous to the PNW and are considered the most widely destructive diseases of wheat in the region. Stripe rust requires cool temperatures, whereas leaf rust requires moderate temperatures. The environment in most areas of the PNW is favorable for stripe rust in 3 out of 4 yr and for leaf rust in 2 out of 4 yr, but in certain specific areas of the PNW, it is always favorable for stripe rust and leaf rust. Stem rust is a warm-temperature disease and is less frequently severe in the PNW. It can, however, be severe when the weather conditions during early and late spring are warm and wet. Models have been developed for predicting the rusts, and guidelines for integrated control have been developed based on laboratory and field research (4,5,11,15).

Common bunt, dwarf bunt, and flag

smut are diseases that have been uniquely important in the PNW. Common bunt, caused by *Tilletia tritici* (Bjerk.) G. Wint. and *T. laevis* Kühn in Rabenh., was the most important disease of wheat in the PNW for the first half of the 20th century. Dwarf bunt, caused by *T. controversa* Kühn in Rabenh., and flag smut, caused by *Urocystis agropyri* (G. Preuss) J. Schröt., are important in specific areas of the PNW. The three smuts are both seedborne and soilborne and are problems in winter wheat; seedborne common bunt can also occur in spring wheat. The smuts are affected by the date of planting in the fall, i.e., early planting reduces common bunt, late planting reduces flag smut, and very late or very early planting reduces dwarf bunt. Treatment of seeds with fungicides is the most effective method for control of common bunt and flag smut. Currently, there is no effective, commercially available seed treatment for control of dwarf bunt, and China has imposed a zero-tolerance quarantine for dwarf bunt on wheat (11). However, difenoconazole, a fungicide currently at the experimental stage, has provided complete control under certain conditions. Therefore, seed treatment may be an important method for control of dwarf bunt in the future.

Cephalosporium stripe, strawbreaker foot rot (Pseudocercosporella foot rot or eyespot), dryland foot rot (Fusarium root and foot rot), Pythium root rot, Rhizoctonia root rot, and take-all are all diseases caused by soilborne pathogens that infect underground plant parts or the basal stem (crown) tissues. These diseases are affected by crop and soil managerial practices (rotation, tillage, planting date, soil moisture, etc.). Most can be reduced by 3-yr rotations and tillage. Strawbreaker foot rot is controlled primarily by resistant cultivars and foliar fungicides; Cephalosporium stripe is reduced by limiting winter wheat to every third year and growing resistant cultivars; and take-all and Pythium root rot may be reduced by tillage and seed treatment. The soilborne nature of these diseases makes their previous occurrence, i.e., disease history, an important aspect of disease management.

Barley yellow dwarf, powdery mildew, the snow molds, and the Septoria diseases occur under certain conditions in some zones and regions of the PNW, and each has its unique epidemiology and control methods. Barley yellow dwarf, transmitted by aphids, is common in zones where wheat is planted early in the fall or late in the spring. Consequently, severity of the disease is affected by aphid activity and population size. Use of insecticides to control the aphids has potential for reducing spread of the disease. Powdery mildew, which is widely distributed throughout the PNW but seldom causes severe damage to wheat, can be controlled by fungicides. The snow molds develop during the winter, especially when there is an extended period of snow cover. Conditions that favor extensive plant growth in the fall reduce potential damage from the disease. Snow molds can be controlled by planting resistant cultivars. The Septoria diseases are most prevalent in regions 4 and 5 where there are long wet periods, especially in the late spring. Crop rotation, cultivar resistance, and/or foliar fungicides control the disease.

Guidelines for managing each disease have been developed and used in the PNW (11). Factors considered in developing the guidelines were: 1) crop and soil managerial systems (regional and local), 2) weather conditions (seasonal, local and regional), 3) kind of diseases and their characteristics, 4) disease and pest interaction, 5) virulence of races and host susceptibility, 6) kind and degree of host resistance, 7) severity of disease at specific growth stages, 8) yield loss in relation to disease severity, 9) effectiveness of fungicides at rates and schedules, 10) potential yield, and 11) economics (costs vs. benefits of control). These factors were used in developing the expert advisory system for wheat disease management.

The Expert Advisory System

Concept of artificial intelligence and expert system. Artificial intelligence is a relatively new concept with definitions that are as varied as the people working with it. Artificial intelligence is defined

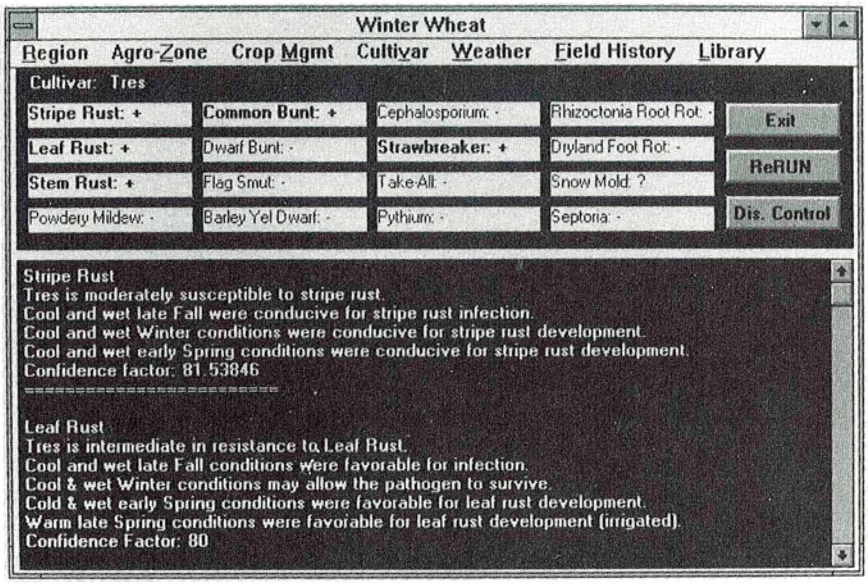

Fig. 4. The predictive disease output appears in a window with two panes. The upper pane lists the diseases that can occur in the field and highlights those that are more likely to occur. The lower pane lists the rationale for the disease outcome and the degree of confidence in the predicted outcome.

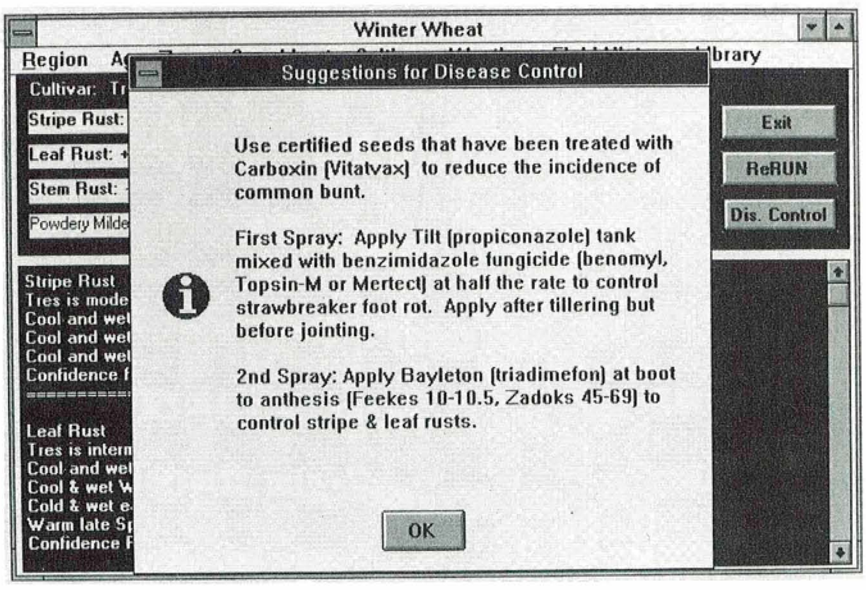

Fig. 5. The dialog box for suggesting a disease control program is displayed when a combination of diseases occurs based on the selected managerial scenario.

as the way of making computers "think" by following the process of how a human mind makes decisions in solving a specific problem (9,10). The human decision-making process is divided into steps, and artificial intelligence programs are designed and structured to follow the same steps to solve complex problems. Included in the broad field of artificial intelligence are visual perception and recognition, robotics, expert systems, natural language processing, learning by noting patterns or exploiting precedents, commonsense reasoning, acoustic perception and interpretation, and software-hardware supercomputing (9,16). Artificial intelligence is also defined as the use of computing techniques and knowledge to generate novel inferences (17). Since artificial intelligence mimics or attempts to mimic the problem-solving process of the human mind, it exhibits functional characteristics such as the capacity to acquire knowledge, the ability to use the acquired knowledge appropriately, the capability to reason out using the acquired knowledge, and the competency to solve complex problems. An artificial intelligence application that uses encoded knowledge from a human expert for a specific domain is referred to as an expert system. Artificial intelligence reasoning and artificial intelligence problem-solving techniques allow expert systems to draw conclusions that were not explicitly programmed into them. An expert system with a well-compiled comprehensive knowledge base can become an extension of one's expertise and serve as a valuable assistant to the user.

Components of MoreCrop. MoreCrop consists of a user interface, a knowledge base, a knowledge acquisition subsystem, an inference engine, a help subsystem, and a library of information related to wheat management (Fig. 3). These components are functionally related to each other. The user interface of MoreCrop takes advantage of the windows environment and allows the user to interact with the system through the graphical screen and icons. This interface enables the user to easily define a managerial scenario by selecting alternatives within the following variables: geographical regions of North America, agronomic zones of the PNW, crop managerial practices, wheat cultivars, seasonal weather, crop and disease history of the field, and disease managerial options. A mouse is used as the pointing device. The keyboard can also be used, but the mouse offers a more efficient and easy way of navigating through the program by simply "pointing and clicking." Menus, control buttons, command buttons, check boxes, icons, graphics, and dynamic-link libraries are the tools that make MoreCrop easy to use.

The knowledge base contains abstract knowledge that is searched by the inference engine. The term abstract knowledge refers to the knowledge of general application and is used in contrast to concrete knowledge, which is knowledge of a specific application (3). The disease susceptibility data for a cultivar is abstract knowledge, whereas the disease reaction of a cultivar due to a selected crop managerial scenario is concrete knowledge. Abstract knowledge is permanently stored, whereas concrete knowledge is ephemeral and is not permanently stored in the system. Concrete knowledge is created by inference and destroyed after use. The agronomic data and disease-susceptibility data of cultivars are part of the abstract knowledge and are stored in a file called Cultivar.DLL, which is loaded directly into the system memory for efficient use of codes. The file Cultivar.DLL is a dynamic-link library written in Pascal, an object-oriented programming language. Object-oriented programming, which is a programming concept that combines data, procedures, and functions to form a new data type called object, is used to define the cultivars. Disease resistance and agronomic characteristics of cultivars, which are defined as objects, are easily manipulated down the procedural hierarchy through encapsulation, inheritance, and polymorphism (2).

The knowledge acquisition subsystem

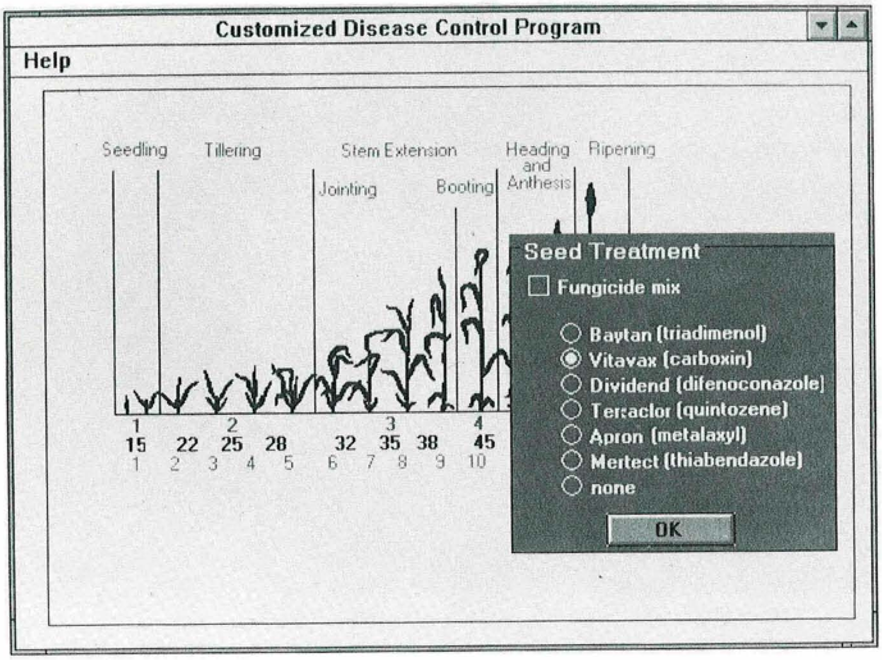

Fig. 6. A frame for seed treatment contains the list of fungicides that can be used for seed treatment.

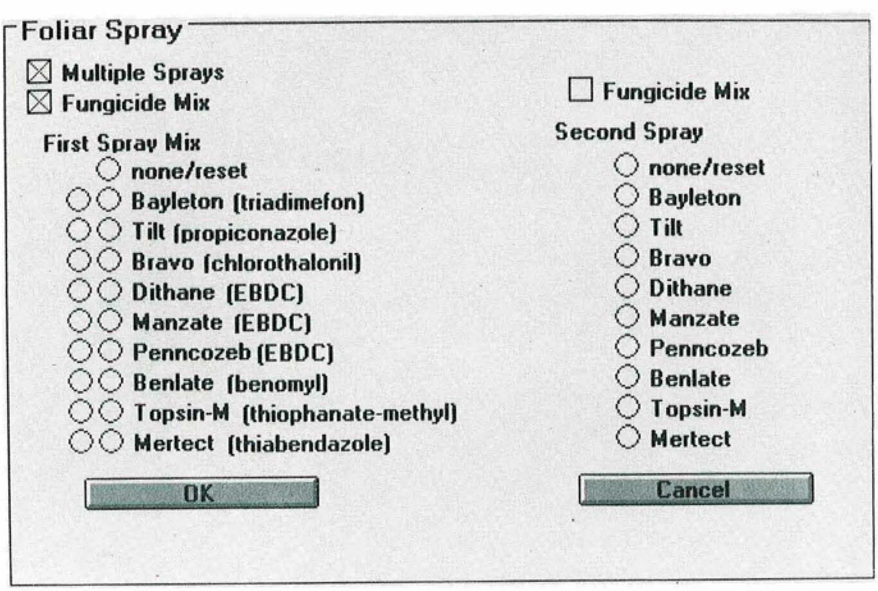

Fig. 7. A frame for foliar spray contains the list of spray fungicides, including choices for mixing fungicides and multiple spraying.

is the learning mechanism of MoreCrop. This component allows addition of new knowledge, rules, and data to the knowledge base in an intelligible form. The knowledge acquisition is not available to the user in the current version of MoreCrop, and access is limited only to the MoreCrop developers. Direct user access to the knowledge acquisition subsystem may be available in future updates of the system.

Inference engine, the protocol for navigating through rules and data, was written in Pascal and programmed to support forward and backward chaining. Forward chaining is an inference method that uses data and information to establish a conclusion. Backward chaining is another inference method that starts from the conclusion and searches for supporting data and information.

The Help subsystem provides on-line help to users by keeping track of the Help handle throughout the program. The Help handle changes in value at various points of the program. The handle serves as the flag indicating the kind of help messages required. Help messages are displayed as dialog boxes without disrupting the flow of the program.

MoreCrop also contains a library of information on the agronomic and disease resistance characteristics of cultivars, the description and distribution of stripe rust races, and the graphical maps of geographical regions and agronomic zones. Warnings, caution statements, and reminders appear in pop-out dialog boxes for added information.

Logic and inference mechanism. MoreCrop uses forward chaining to tell what diseases are more likely to occur based on the selected managerial practices, cultivar, geographical region, agronomic zone, prevailing weather, and crop and disease history of the field. Backward chaining provides the reasons for the disease outcome by tracking backward through the managerial options and the status of variables that support the disease outcome. Backward chaining organizes and provides the backtracked data as the rationale for a disease outcome.

Three inference engines are fired in sequence to provide information related to a specific crop managerial scenario. The first inference engine, Predictor, considers the classical disease triangle as the overriding principle in predicting diseases. Thus, for a disease to occur there should be a susceptible host, a virulent pathogen, and a favorable environment for disease development. Selection of a wheat cultivar may determine the susceptibility or resistance of the host, and disease history may indicate the presence of a virulent pathogen. Crop managerial practices along with the prevailing weather determine the favorability of the environment for disease development. Predictor provides a list of diseases that may occur and highlights in bold type those that are more likely to occur based on the region, zone, crop management (rotation, tillage, irrigation, planting date, and fertility management), cultivar, weather (early fall, late fall, winter, early spring, and late spring), and crop and disease history of the field (Fig. 4). Information related to disease control and the rationale for the disease outcome are dynamically linked to the specific diseases and are available to the user on demand by pointing and clicking. The rationale for the disease outcome, which is constructed by backward chaining, lists the reasons why each disease in bold type may or may not occur (Fig. 4, lower windowpane). A confidence factor, which expresses the degree of confidence that the disease will occur, is also shown.

The second inference engine, Controller, makes suggestions for integrated disease management (IDM). The output of Predictor is used by Controller as the initial input for the IDM options or suggestions. Controller considers the diseases that are more likely to occur and evaluates the various disease control options from the knowledge base. The disease control options include a seed treatment, kind of seed treatment fungicide, one or two foliar sprays, kind of foliar fungicide, tank-mixed sprays,

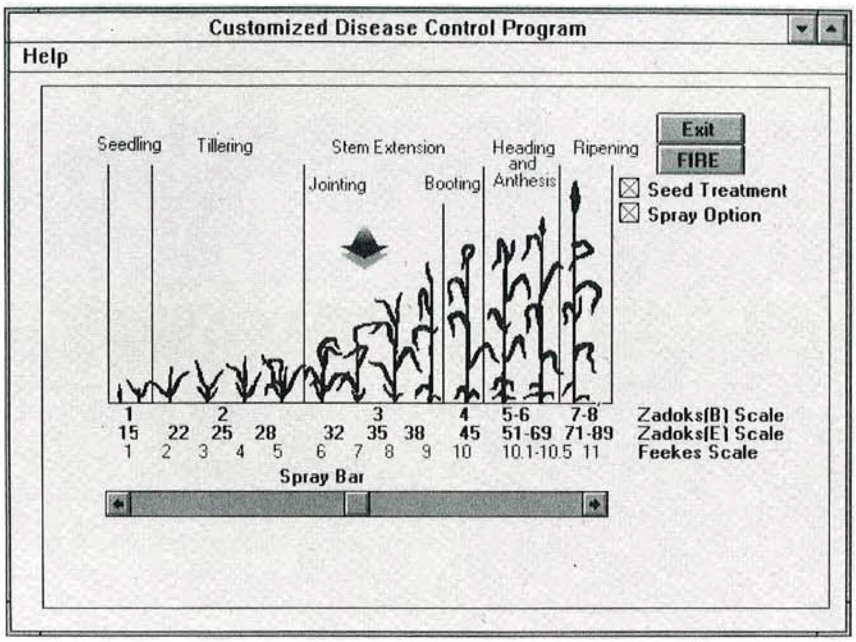

Fig. 8. A graphical display of the entire cropping season is represented by growth stages. The location of the spray arrow in relation to the scales corresponds to the timing of spray.

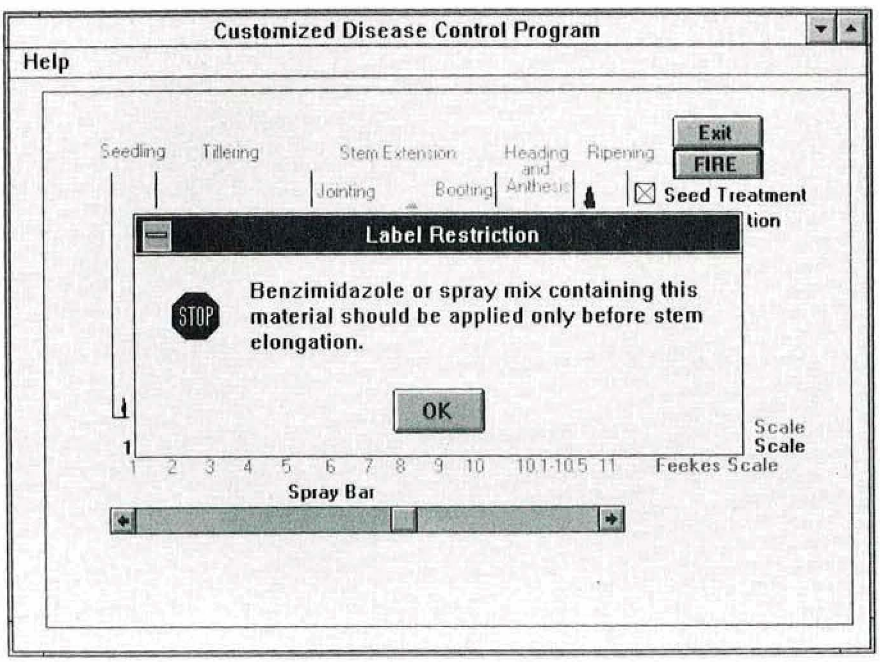

Fig. 9. Warning or caution statements appear in a dialog box when conflicts occur.

tank-mixed compatibility, label restrictions, timing of spray application, and benefits from spraying based on potential yield. Controller determines the best disease control option and suggests a program for control of the diseases that were predicted based on the selected crop managerial scenario (Fig. 5).

The third inference engine, CustomController, provides flexibility and independence in managing wheat diseases. CustomController provides options for seed treatment (Fig. 6) and foliar sprays (Fig. 7). A graphical display of crop stages allows the user to customize timing of spray applications by graphically positioning a spray arrow at any plant growth stage (Fig. 8). Warning and caution statements in dialog boxes may appear when a managerial decision conflicts with a pesticide label restriction (Fig. 9). CustomController evaluates the control program that was tailored by the user and provides a list of diseases that cannot be controlled and diseases that can be controlled by the customized disease control program (Fig. 10). The rationale for disease control or absence of disease control is also linked to the list of diseases in order to provide information on why the tailored disease control program succeeded or failed. CustomController provides an unlimited opportunity to change the managerial decisions and recustomize the disease control program.

Program Expansion and Updates

The first version of MoreCrop was released on March 1992 to wheat growers, extension agents, industry representatives, plant pathologists, soil and crop scientists, and others who were interested in evaluating the program. That version of the program automatically recorded all the keystrokes of the users, and it contained a survey form where users typed their comments, suggestions for improvement, and reports of "bugs" and other problems. Suggestions from these evaluators were used to redesign and improve the program. Updates on the program will continue on a regular basis as new information becomes available. Since most of the information components of MoreCrop are available as dynamic-link libraries (DLL), an update would not require drastic changes in codes. For instance, the wheat cultivars and their characteristics were supplied in a DLL (Cultivar.DLL). When the resistance or susceptibility of a cultivar changes due to the evolution of new races of the pathogen or other factors, the program can be updated by merely editing the DLL file. In the same way, when a newly developed wheat cultivar is released for commercial use, the new cultivar with all its characteristics is simply added to the DLL file. Portability and reusability of codes were clear advantages of using DLL in the program. Since the DLL is language-independent, it can be used by applications written in other languages to address the same set of functions and procedures. The DLL can provide data on wheat cultivar characteristics (agronomic and disease susceptibility) to other applications requiring that information.

MoreCrop is flexible and extendable. High resolution images of wheat diseases can be incorporated and displayed interactively. A powerful relational database can be constructed to contain records of cultivar characteristics, performance of cultivars at various locations and years, farm pesticide applications, material safety data sheets, farm budgets, and other farm records. The current version of the program contains provisions for displaying images and linking to a database. The program can also be extended to include fertility management and management of other pests such as weeds and insects. Thus, MoreCrop can serve as a prototype in developing a total program for wheat management. The programming structure of MoreCrop and the visual controls as well as the concepts and principles should be easily adapted for use in managing other crops or for use in other regions of the world.

MoreCrop requires an IBM PS/2 or IBM-compatible computer with 386 or 486 microprocessor, at least 4 MB of RAM, and Microsoft Windows 3.0 or later version. A 3.5-in. high-density floppy disk and a hard disk with at least 3.0 MB of free disk space are needed. MoreCrop comes with a setup procedure that automatically installs the whole program to the system. The setup procedure creates the directory MoreCrop (default), loads the executable file (MCrop1.Exe) along with the supporting graphics and text files, and creates a program group with the MoreCrop icon in the Windows Program Manager.

Applications of MoreCrop

MoreCrop provides information, options, and suggestions to help the user make decisions regarding management of wheat diseases. Sixteen important diseases in the PNW can be predicted on the basis of geographical regions, agronomic zones, crop managerial practices, cultivar characteristics, field history, and prevailing weather. MoreCrop can use past managerial decisions to reconstruct previous disease conditions, assist the user in reasoning what disease control option to select, recommend a disease control program for a specific disease, suggest an integrated disease managerial program based on a given set of diseases, allow the user to design a customized disease control program, evaluate the user's customized disease control program designed for a specific managerial scenario, and provide disease-related as well as cultivar-related information for research, education, and extension. MoreCrop can be used as a decision support system by wheat growers, extension agents, consultants, and other professionals involved in wheat management. The program contains up-to-date information relating to wheat cultivars and their characteristics, agronomic zones, fungicide technical information (1), crop managerial options, a list of stripe rust races, distribution of stripe rust races, description of stripe rust races, and other subject matters relevant to wheat production in the PNW. This information is easily accessible by pointing and clicking. MoreCrop can

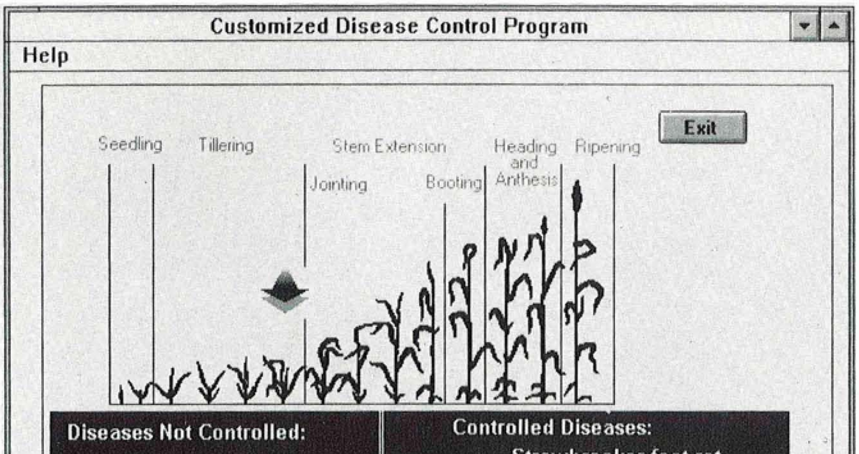

Fig. 10. A user-defined disease control program is evaluated and MoreCrop lists the diseases that are controlled as well as the diseases that are not controlled by the customized disease control program.

also be used as an educational tool for managing wheat diseases and as a training and reference tool to solve real-time problems.

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